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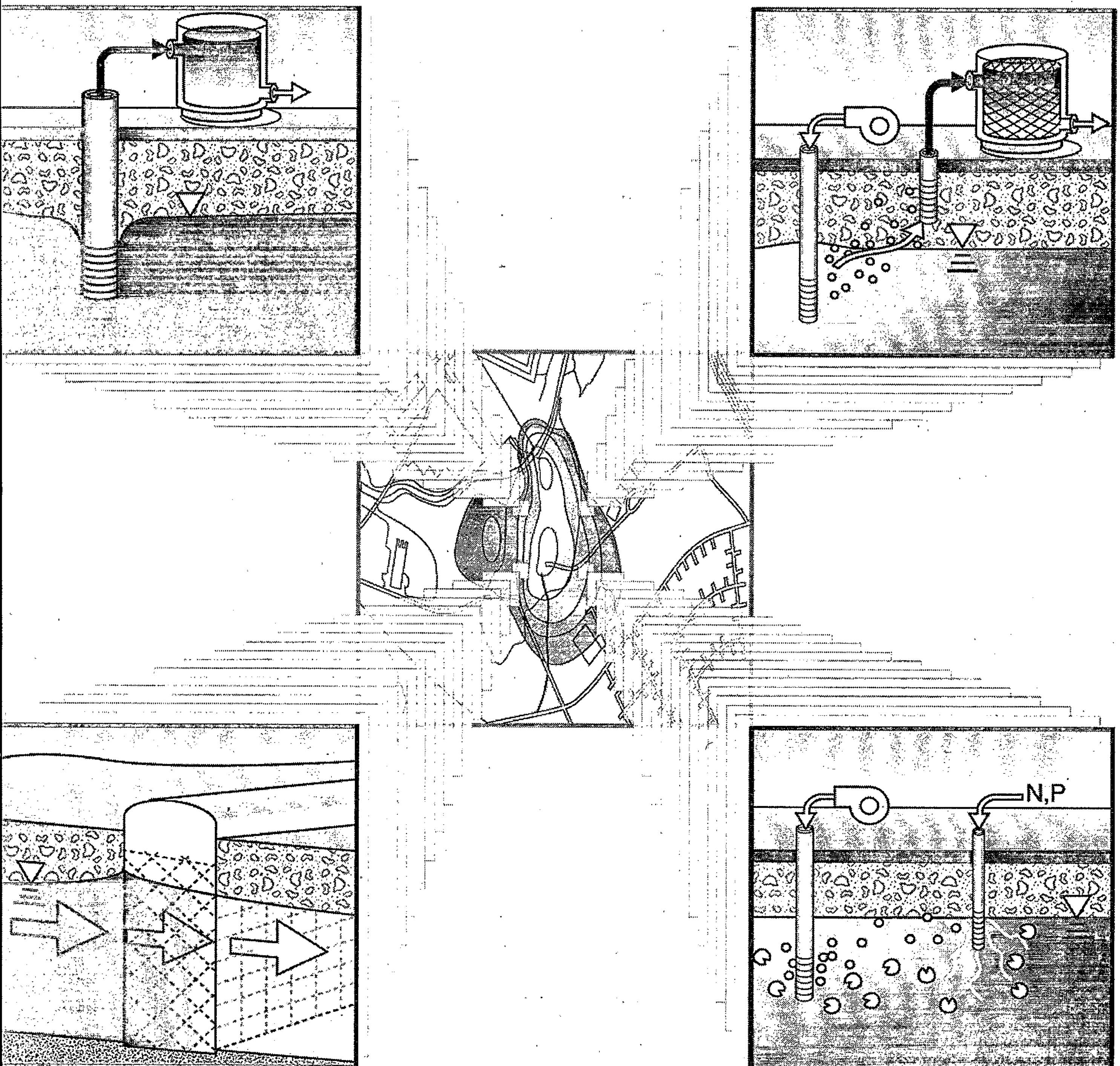
Groundwater Cleanup: Overview of Operating Experience at 28 Sites



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Groundwater Cleanup:
Overview of Operating Experience at 28 Sites

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
Washington, DC 20460

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ACKNOWLEDGMENTS

Special acknowledgment is given to the remedial project managers, potentially responsible parties, and vendors involved at the case study sites for their thoughtful suggestions and support in preparing the individual case studies and in contributing to this report.

EXECUTIVE SUMMARY

This study examined operating experiences at 28 sites across the United States at which completed or ongoing groundwater cleanup programs are in place. Although not a representative sample, the sites present a range of the types of cleanups typically performed at sites with contaminated groundwater. At 21 of the sites, pump-and-treat (P&T) systems were used alone as the remediation technology; at two of the sites, permeable reactive barriers (PRBs), an *in situ* technology, were used alone as the remediation technology. In addition, *in situ* technologies were used in conjunction with P&T at five sites, including one site with P&T that was replaced with a PRB. Individual reports have previously been published for each of the 28 sites by the Federal Remediation Technology Roundtable and are available at <*www.frtr.gov/cost*>.

Of the 28 case study sites, 24 are Superfund remedial actions, one is a Superfund removal action, one is a state cleanup, and two are Resource Conservation and Recovery Act (RCRA) corrective actions. Chlorinated solvents are the type of contaminant most frequently present, found at 21 of the 28 sites. The sites are located throughout the U.S. and include a range of site types and hydrogeological conditions. For example, nonaqueous phase liquids (NAPL) were observed or suspected to be present at 18 of the 28 sites, and hydraulic conductivity varied among the sites by more than six orders of magnitude.

This report summarizes information about the groundwater remediation systems at the 28 sites, including: design, operation, and performance of the systems; capital, operating, and unit costs of the systems; and factors that potentially affect the cost and performance of the systems. Data from the case studies are compared and contrasted to assist those involved in evaluating and selecting remedies for groundwater contamination at hazardous waste sites.

Data on performance through late 1997/early 1998 compiled for the report show that total contaminant removal at the case study sites ranged from seven pounds to more than 510,000 pounds with a median contaminant mass removal of 2,000 pounds. The average annual volume of groundwater treated ranged from 1.7 million to 550 million gallons (at P&T sites). Although remediation has been completed at only two of the 28 sites, at the 26 sites with ongoing remediation, progress has been made toward achieving cleanup goals, including: reducing the size of a contaminated plume; reducing or eliminating a hot spot within a plume; reducing the concentrations of contaminants within a plume; removing contaminant mass from a plume; and achieving containment of a plume.

Capital and operating and maintenance (O&M) costs at the case study sites through late 1997/early 1998 also were compiled for this report. Although P&T and PRB systems may be designed to accomplish similar remedial goals, the spatial area of groundwater they treat is generally different; therefore, their costs are presented separately in this report. For the 26 P&T systems, the approximate median capital cost was $1.9 million and the median average annual operating cost was $190,000; with median unit costs of $96 of capital cost per average 1,000 gallons of groundwater treated per year and $18 of average annual operating cost per average 1,000 gallons of groundwater treated per year. For the three PRB systems, the approximate median capital cost was $500,000 and the median average annual operating cost was $85,000; with median unit costs of $520 of capital cost per average 1,000 gallons of groundwater treated per year and $84 of average annual operating cost per average 1,000 gallons of groundwater treated per year.

Since the sites summarized in this report were not selected as a representative sample of all groundwater cleanup sites, the medians, averages, and ranges calculated in this report should not be used to draw generalizations about cost and performance at other groundwater cleanup sites.

Results of analyses of the case studies showed that the factors affecting cost and performance and the extent of the effect of those factors varied from site to site. However, based on the information provided for the 28 case study sites and general observations of groundwater cleanup as a whole, the following factors have a significant effect on the cost and performance of groundwater remediation systems.

- **Source control factors** - Method, timing, and success of source controls to mitigate contact of NAPLs or other contaminant sources, such as highly contaminated soil, with groundwater

- **Hydrogeologic factors** - Aquifer properties that define contaminant transport and groundwater extraction system design needs, including hydraulic connection of aquifers that allows for multi-aquifer contamination, aquifer flow parameters, influences from adjacent surface water bodies on the aquifer system, and influences of adjacent groundwater production wells on the aquifer system

- **Contaminant property factors** - Contaminant properties that define the relative ease that contaminants may be removed from the aquifer, the steps that are required to treat the extracted groundwater, and the complexity of the contaminant mixture

- **Extent of contamination factors** - The magnitude of the contaminated groundwater plume, including the plume area and depth and the concentrations of contaminants within the plume

- **Remedial goal factors** - Regulatory factors that affect the design of a remedial system and/or the duration that it must be operated, including defining aquifer restoration or treatment system performance goals and specific system design requirements, such as disallowing reinjection of treated groundwater or specifying the treatment technology to be used

- **System design and operation factors** - The adequacy of a system design to remediate the site, system downtime, system optimization efforts, the amount and type of monitoring performed, and the use of *in situ* technology to replace or supplement a P&T system

Specific examples of how each of these factors affected the cost and performance of the groundwater remediation systems at the case study sites are cited within this report.

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LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

AS	Air sparging
ACL	Alternate concentration limit
BTEX	Benzene, toluene, ethylbenzene, and xylene
DCE	Dichloroethene
DNAPL	Dense nonaqueous phase liquid
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ISB	*In situ* bioremediation
LNAPL	Light nonaqueous phase liquid
MCL	Maximum contaminant level
NAPL	Nonaqueous phase liquid
NPV	Net present value
OSWER	Office of Solid Waste and Emergency Response
P&T	Pump and treat
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
POTW	Publicly-owned treatment works
PRB	Permeable reactive barrier
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision
SVOC	Semivolatile organic compound
TCE	Trichloroethene
TIO	Technology Innovation Office
USCG	United States Coast Guard
VCB	Vertical containment barrier
VOC	Volatile organic compound

1.0 INTRODUCTION

Groundwater contamination is present at the majority of Superfund and Resource Conservation and Recovery Act (RCRA) corrective action sites. Groundwater remediation technologies currently in use to clean up these sites include pump-and-treat (P&T) systems, and *in situ* technologies such as bioremediation, permeable reactive barriers, and air sparging. As part of an effort by the Federal Remediation Technologies Roundtable,[1] the U.S. Environmental Protection Agency (EPA) has prepared 28 case studies of ongoing and completed groundwater remediation projects. The Roundtable has published these case studies, along with 112 other case studies about a wide range of technologies, which are available through the Internet at *<www.frtr.gov/cost>*, or in hard copy through the EPA National Service Center for Environmental Publications (NSCEP). Case studies are about 10-20 pages in length and contain information about site background, extent of contamination, technology design and operation, performance, cost, observations and lessons learned, and points of contact for further information.

The objective of this report is to provide a summary of information about the 28 groundwater remediation case studies, including comparing results among sites, to further assist those involved in evaluating and selecting remedies for groundwater contamination at hazardous waste sites. The case studies present a range of the type of cleanups typically performed at groundwater-contaminated sites, and include 21 sites with P&T systems alone, four sites with P&T systems supplemented with *in situ* technologies, one site with P&T that was replaced by an *in situ* technology, and two systems with only *in situ* technologies. The majority of the case studies are ongoing projects, with remediation completed at two of the sites.

The report presents an overview of each of the case study sites (Section 2); describes the design and operation of the remediation systems, including efforts to optimize the systems (Section 3); summarizes the performance of each of the systems at the sites, including final results for completed remediations and progress towards goals for ongoing projects (Section 4); examines the costs for these systems, including capital, operating, and unit costs (Section 5); and examines the factors that potentially affect the cost or performance of the remediation systems (Section 6). References used to prepare this report are listed in Section 7 and are cited in parentheses.

As described in Section 2 of this report, the case study sites were selected in part on the basis of availability of information. Therefore, it is important to note that the case studies are not intended to be a representative sample of groundwater remediation projects; rather, they present a range of the types of systems that are being used at Superfund and RCRA corrective action sites. Further, this report is not intended to revise or update EPA policy or guidance on how to clean up sites with contaminated groundwater.

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[1] The Federal Remediation Technologies Roundtable consists of senior executives from eight agencies with an interest in site remediation, including the U.S. Army, the U.S. Navy, the U.S. Air Force, the U.S. Department of Energy (DOE), and EPA. The Roundtable, which was created to build a more collaborative atmosphere among federal agencies involved in the remediation of hazardous waste sites, has on ongoing effort to improve the type and availability of cost and performance information for site remediation technologies. This information is being provided to assist those involved in evaluating and selecting remedies for hazardous waste cleanups.

2.0 OVERVIEW OF 28 CASE STUDY SITES

- Sites are located throughout the U.S. and include a range of site types and hydrogeological conditions
- At some sites, groundwater remediation has been ongoing since the late 1980s
- Chlorinated solvents are the most common contaminant

The 28 groundwater case study sites included in this report were selected from a list of candidate sites that was developed using information from previous work by EPA and recommendations by EPA regional staff. The following criteria were used in selecting the specific sites:

- Sites at which groundwater cleanup systems had been operated for a relatively long period of time
- Sites for which aquifer cleanup goals (not only containment goals) had been established
- Sites for which sufficient cost and performance data were available

Exhibit 2-1 summarizes general information about each of the 28 sites, such as duration and status of remediation, categories of contaminants targeted for treatment, type of cleanup, project lead, and highlights of the project. Of the 28 sites, 24 are Superfund remedial actions, one is a Superfund removal action, one is a state cleanup, and two are Resource Conservation and Recovery Act (RCRA) corrective actions. Of the 25 Superfund sites, four are EPA led, one is U.S. Navy led, 11 are potentially responsible party (PRP) led, and nine are state led. The sites have been grouped by the type of contamination that was targeted for cleanup at each (volatile organic compounds [VOC], VOCs combined with other contaminants, or metals).

Exhibit 2-2 presents the years of operation at each site. Groundwater remediation at most of the case study sites is ongoing, with systems operating over periods ranging from two years (*USCG Center* and *Moffett*) to 11 years (*Des Moines* and *Former Intersil*). Cleanup has been completed at two of the sites (*Firestone* and *Gold Coast)* and the remediation systems at three other sites (*French Ltd.*, *Sol Lynn*, and *Sylvester/Gilson Road*) have been shut down for various reasons, although the cleanups at these sites are not considered complete. At one site (*Western Processing*), the goal has been changed from restoration to containment. Nine of the 28 systems have been operating since the late 1980s. For sites at which systems are ongoing, the information presented in the report is current as of late 1997 or early 1998.

Exhibit 2-3 shows the type of site and the relative location of each site.

Exhibit 2-1: Summary of 28 Case Study Sites

Site Name, Location, CERCLIS ID no.	Duration/Years of System Operation[1]	Remediation Status	Contaminant Categories Targeted for Treatment	Type of Cleanup[2]	Lead(s)	Site Highlight(s)
VOCs CONTAMINATION						
City Industries SF Site, FL (City Industries) CERCLIS #FLD055945653	4.0	Ongoing	VOCs	SF Remedial	PRP	Simple hydrogeology with relatively high hydraulic conductivity; pumping optimization modeling used
Des Moines TCE SF Site, IA (Des Moines) CERCLIS #IAD98060687933	10.5	Ongoing	VOCs	SF Remedial	PRP	Approximately 5 billion gallons treated to date to contain and remediate contaminated groundwater; dense nonaqueous phase liquid (DNAPL) suspected
Former Firestone Facility SF Site, CA (Firestone) CERCLIS #CAD990793887	7.0	Complete	VOCs	SF Remedial	PRP	Groundwater cleanup completed in seven years
Former Intersil Inc., CA (Intersil)	10.5	Ongoing	VOCs	State Cleanup	PRP	Used P&T for eight years; replaced that technology with permeable reactive barrier to minimize cost of treatment while increasing effectiveness of treatment, and to return site to leasable or sellable conditions
French, Ltd. SF Site, TX (French, Ltd.) CERCLIS #TXD980514814	4.0	Monitored Natural Attenuation	VOCs	SF Remedial	PRP	Regulatory requirements set as demonstrating, through modeling, that cleanup goals would be met at site boundary via monitored natural attenuation 10 years after P&T is completed
Gold Coast SF Site, FL (Gold Coast) CERCLIS #FLD071307680	3.5	Complete	VOCs	SF Remedial	EPA	Air sparging used to remediate recalcitrant area of contamination at the end of the cleanup, optimization modeling used
JMT Facility RCRA Site (formerly Black & Decker), NY (JMT)	10.0	Ongoing	VOCs	RCRA CA	Owner/Operator	Included use of an artificially produced fracture zone in the bedrock

Table Continued...

Notes:
[1] Years of system operation as of end of June 1998
[2] SF indicates Superfund site; RCRA CA indicates RCRA corrective action site

Exhibit 2-1: Summary of 28 Case Study Sites

Site Name, Location, CERCLIS ID no.	Duration/Years of System Operation[1]	Remediation Status	Contaminant Categories Targeted for Treatment	Type of Cleanup[2]	Lead(s)	Site Highlight(s)
Keefe Environmental Services SF Site, NH (Keefe) CERCLIS #NHD092059112	5.5	Ongoing	VOCs	SF Remedial	State	Major modifications to system design based on optimization study
Moffett Federal Airfield SF Site, CA (Moffett)	2.0	Pilot Scale Ongoing	VOCs	SF Remedial	U.S. Navy	Permeable reactive barrier successful in reducing trichloroethene (TCE) concentrations; increased monitoring required for technology certification and validation
Mystery Bridge at Highway 20 SF Site, WY (Mystery Bridge) CERCLIS #WYD981546005	4.5	Ongoing	VOCs	SF Remedial	EPA	Monitored natural attenuation used for remedy of the off-site portion of the plume
Old Mill SF Site, OH (Old Mill) CERCLIS #OHD980510200	9.0	Ongoing	VOCs	SF Remedial	EPA	System of trenches used to extract shallow groundwater
SCRDI Dixiana SF Site, SC (SCRDI Dixiana) CERCLIS #SCD980711394	6.0	Ongoing	VOCs	SF Remedial	EPA '92-'94 PRP '95-present	Complex hydrogeology; major modifications made in system by PRP
Site A (Confidential SF Site), NY (Site A) CERCLIS #Confidential	3.0	Ongoing	VOCs	SF Remedial	State	Remedial system included use of P&T supplemented with air sparging and *in situ* bioremediation
Sol Lynn/Industrial Transformers SF Site, TX (Sol Lynn) CERCLIS #TXD980973327	3.0	Shut Down Pending Study	VOCs	SF Remedial	State	Multiaquifer contamination (three aquifers); additional contamination identified after remediation began
Solid State Circuits SF Site, MO (Solid State) CERCLIS #MOD9808854111	5.4	Ongoing	VOCs	SF Remedial	State	Complex hydrogeology (leaky artesian system in a Karst formation)
U.S. Aviex SF Site, MI (U.S. Aviex) CERCLIS #MID980794556	5.0	Ongoing	VOCs	SF Remedial	EPA '93-'96 State '96-present	Performance modeling used for system optimization

Table Continued...

Notes:
[1] Years of system operation as of end of June 1998
[2] SF indicates Superfund site; RCRA CA indicates RCRA corrective action site

Exhibit 2-1: Summary of 28 Case Study Sites

Site Name, Location, CERCLIS ID no.	Duration/Years of System Operation[1]	Remediation Status	Contaminant Categories Targeted for Treatment	Type of Cleanup[2]	Lead(s)	Site Highlight(s)
VOCs COMBINED WITH OTHER CONTAMINANTS						
Baird and McGuire SF Site, MA (Baird and McGuire) CERCLIS #MAD001041987	5.5	Ongoing	VOCs, semivolatile organic compounds (SVOCs), pesticides, metals	SF Remedial	EPA	Complex mixture of contaminants requiring extensive treatment train
King of Prussia Technical Corporation SF Site, NJ (King of Prussia) CERCLIS #NJD980505341	3.5	Ongoing	VOCs, metals	SF Remedial	PRP	Complex mixture of contaminants requiring extensive treatment train
LaSalle Electrical SF Site, IL (LaSalle) CERCLIS #SCD980711394	5.5	Ongoing	VOCs, polychlorinated biphenyls (PCBs)	SF Remedial	State	Relatively low groundwater flow; DNAPLs present
Libby Groundwater SF Site, MT (Libby) CERCLIS #MTD980502736	7.0	Ongoing	VOCs, SVOCs	SF Remedial	PRP	Light nonaqueous phase liquids (LNAPLs) and DNAPLs perpetuate elevated levels of contaminants in groundwater
Mid-South Wood Products SF Site, AR (MSWP) CERCLIS #ARD092916188	9.0	Ongoing	VOCs, SVOCs	SF Remedial	PRP	System optimization performed after eight years of operation; contamination reduced to one localized area of concern
Solvent Recovery Services of New England, Inc. SF Site, CT (Solvent Recovery Service) CERCLIS #CTD009717604	3.0	Ongoing	VOCs, metals	Removal	PRP	Complex mixture of contaminants having various properties led to extensive treatment train; DNAPLs present
Sylvester/Gilson Road SF Site, NH (Sylvester/Gilson Road) CERCLIS #NHD099363541	9.5	Shut Down Pending Explanation of Significant Difference (ESD)	VOCs, pesticides, metals	SF Remedial	State	Modifications of the system were costly; system shut down since 1996, pending an ESD to raise the alternate concentration limit (ACL) for 1,1-dichloroethane to greater than method detection limit

Table Continued...

Notes:
[1] Years of system operation as of end of June 1998
[2] SF indicates Superfund site; RCRA CA indicates RCRA corrective action site

Exhibit 2-1: Summary of 28 Case Study Sites

Site Name, Location, CERCLIS ID no.	Duration/Years of System Operation[1]	Remediation Status	Contaminant Categories Targeted for Treatment	Type of Cleanup[2]	Lead(s)	Site Highlight(s)
USCG Support Center, NC (USCG Center)	2.0	Ongoing	VOCs, metals	RCRA CA	Owner/Operator	Use of PRB to treat groundwater contaminated with TCE and hexavalent chromium; extensive sampling conducted to evaluate
Western Processing SF Site, WA (Western Processing) CERCLIS #WAD009487514	10.0	Ongoing	VOCs, metals	SF Remedial	PRP	Goals for off-site plume met; on-site system modified to provide containment of on-site contamination rather than site restoration; NAPL observed and suspected in various areas of the site
METALS CONTAMINATION						
Odessa Chromium I SF Site, TX (Odessa I) CERCLIS #TXD980867279	4.5	Ongoing	metals	SF Remedial	State	Low groundwater production; electrochemical treatment for chromium required by Record of Decision (ROD)
Odessa Chromium IIS SF Site, TX (Odessa IIS) CERCLIS #TXD980697114	4.5	Ongoing	metals	SF Remedial	State	Relatively low groundwater production; multiaquifer contamination; electrochemical treatment for chromium required by ROD
United Chrome SF Site, OR (United Chrome) CERCLIS #ORD009043001	10.0	Ongoing	metals	SF Remedial	PRP	Contaminant concentrations reduced to the point at which extracted groundwater can be discharged to the publicly-owned treatment works (POTW) without on-site treatment; major modifications made in extraction system

Notes:
[1] Years of system operation as of end of June 1998
[2] SF indicates Superfund site; RCRA CA indicates RCRA corrective action site

Exhibit 2-2: Remediation Systems - Years of Operation

Site Name, Location	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	Years Operating
Former Firestone Facility SF Site, CA								1						7
Sylvester/Gilson Road SF Site, NH											2			9.5
Former Intersil Inc., CA														10.5
Des Moines TCE SF Site, IA														10.5
JMT Facility RCRA Site (formerly Black & Decker), NY														10
United Chrome SF Site, OR														10
Western Processing SF Site, WA														10
Old Mill SF Site, OH														9
Mid-South Wood Products SF Site, AR														9
Gold Coast SF Site, FL									1					3.5
Libby Groundwater SF Site, MT														7
French, Ltd. SF Site, TX											3			4
SCRDI Dixiana SF Site, SC														6
LaSalle Electrical SF Site, IL														5.5
Solid State Circuits SF Site, MO														5.5
Baird and McGuire SF Site, MA														5.5
Keefe Environmental Services SF Site, NH														5.5
U.S. Aviex SF Site, MI														5
Sol Lynn/Industrial Transformers SF Site, TX												4		3
Odessa Chromium I SF Site, TX														4.5
Odessa Chromium IIS SF Site, TX														4.5
Mystery Bridge at Highway 20 SF Site, WY														4.5
City Industries SF Site, FL														4
King of Prussia Technical Corporation SF Site, NJ														3.5
Solvent Recovery Services of New England, Inc. SF Site, CT														3
Site A (Confidential) SF Site, NY														3
Moffett Federal Airfield SF Site, CA														2
USCG Support Center, NC														2

Notes:

- Indicates ongoing cleanups.
- 1 Groundwater cleanup is complete.
- 2 Sylvester/Gilson Road system was shut down pending an Explanation of Significant Difference.
- 3 French Limited cleanup continues by natural attenuation since 12/95. Cleanup is not complete.
- 4 Sol Lynn system was shut down for maintenance and upgrade in 10/96. Cleanup is not complete.

Exhibit 2-3: Site Types and Locations

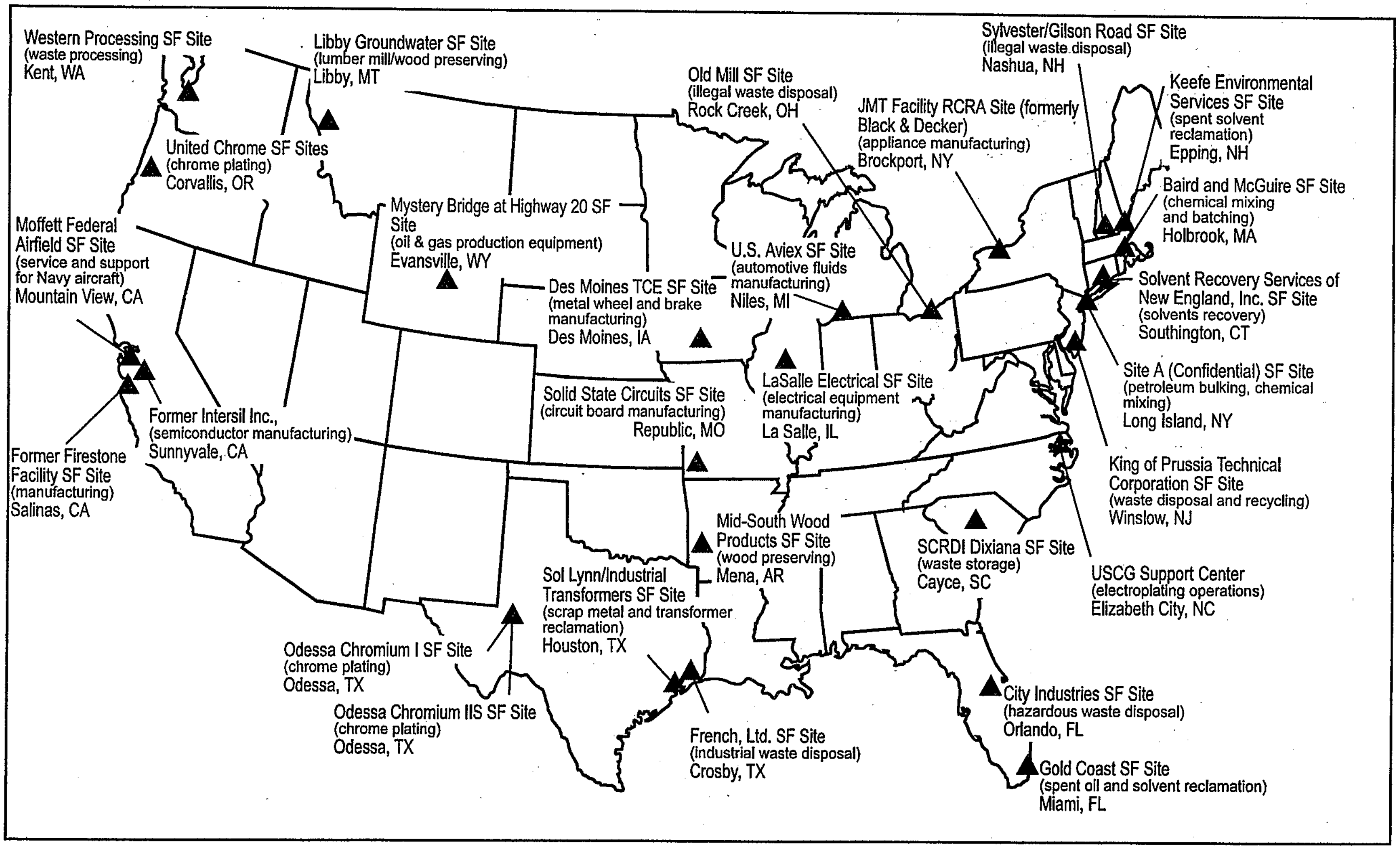


Exhibit 2-4 summarizes the types of contaminants treated at the 28 sites. The contaminants fall into the following categories. Multiple contaminant category groups have been targeted for treatment at some sites.

- Volatile organic compounds (VOCs)
  - Chlorinated VOCs
  - Benzene, toluene, ethylbenzene, and xylene (BTEX)
  - Other VOCs
- Semivolatile organic compounds (SVOCs)
  - Pesticides
  - Polycyclic aromatic hydrocarbons (PAHs)
  - Polychlorinated biphenyls (PCBs)
  - Other SVOCs
- Metals

Chlorinated VOCs were the type of contaminant most frequently present, found at 21 of the 28 sites.

Exhibit 2-5 summarizes information about the specific contaminants addressed at the sites. Only contaminants that were treated at more than one site are included in this exhibit. Six of the 10 most common contaminants treated were chlorinated VOCs, with trichloroethene (TCE), treated at 18 sites, the most common. Benzene was the most commonly treated nonchlorinated VOC (at five sites). Chromium was the most common metal, treated at seven of the sites.

Exhibit 2-6 shows the volume of the contaminated groundwater plume at each site. For most of the sites, the extent of contamination was quantified by the volume of contaminated groundwater. Plume volume presented for these sites generally represents one pore volume of the contaminated plume prior to commencing groundwater cleanup activities at the site. The volume was calculated by the site contractors or during the preparation of the cost and performance reports by combining isoconcentration data for groundwater contaminants with reported or typical hydrogeological data. The volume of contaminated groundwater at the sites ranged from 930,000 gallons (*Intersil*) to 5.6 billion gallons (*Moffett*). The average volume of the contaminated plume was 440 million gallons, and the median volume was 29 million gallons.

Exhibit 2-4: Categories of Contaminants Treated at 28 Sites

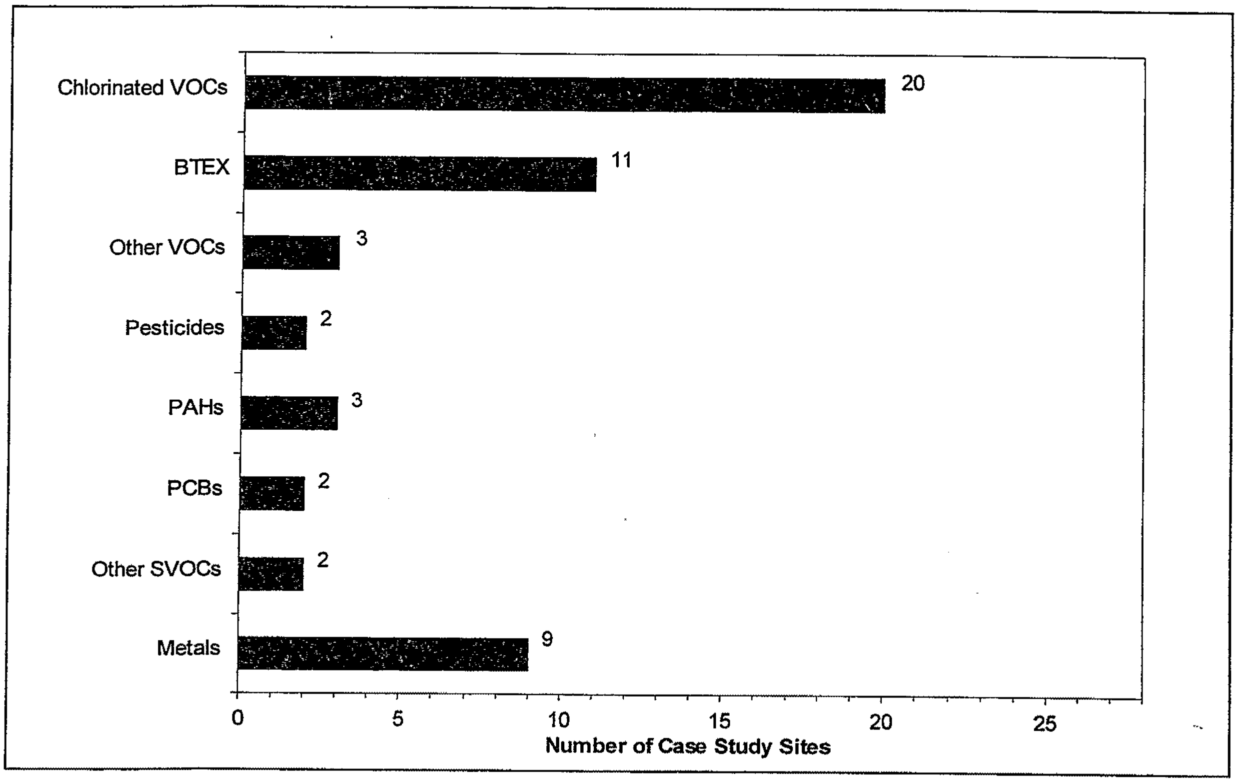


Exhibit 2-5: Specific Contaminants Treated at 28 Sites

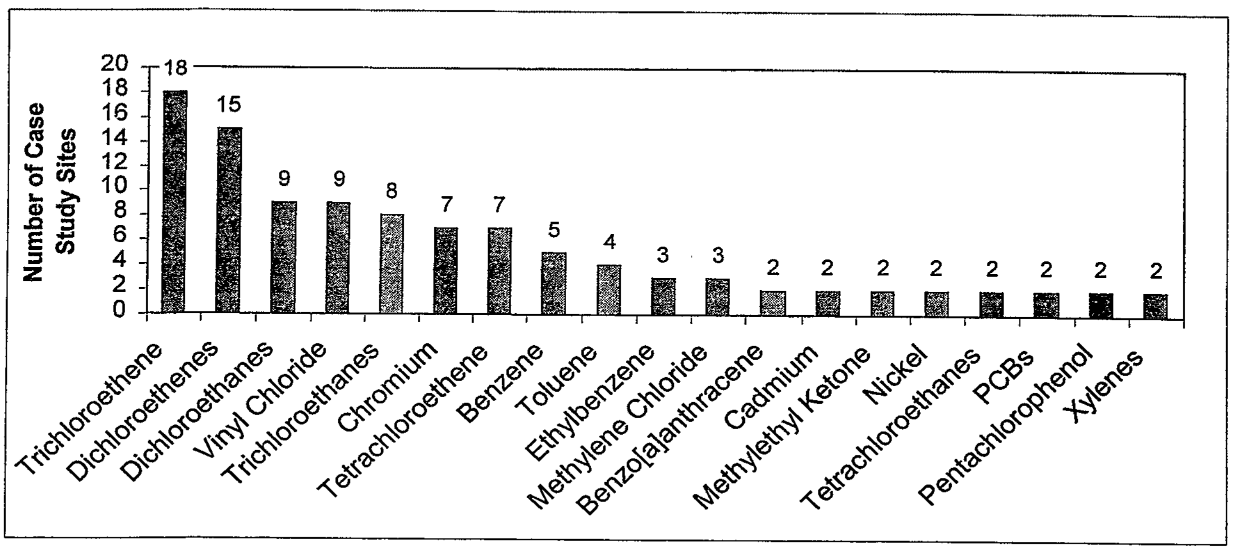
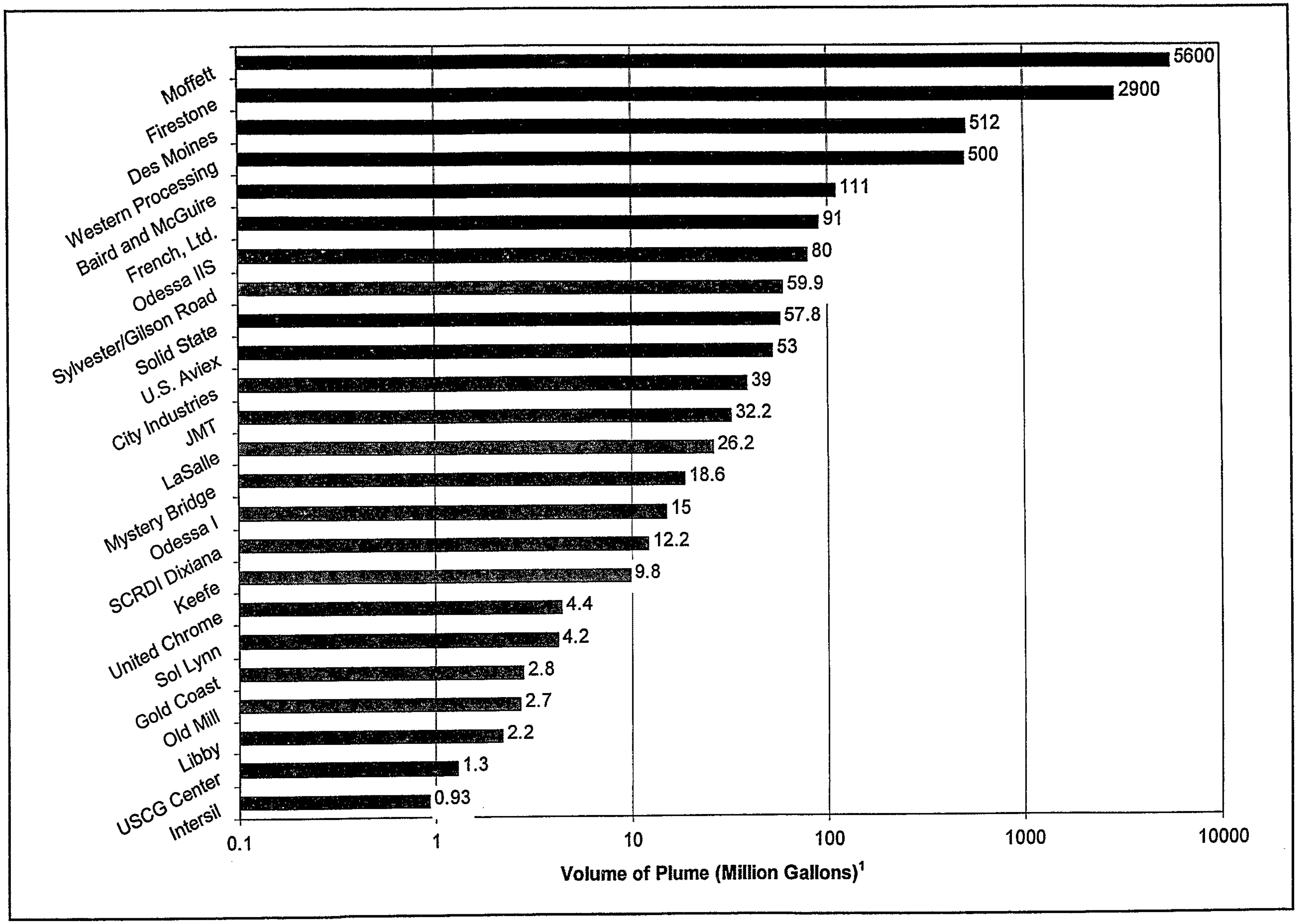


Exhibit 2-6: Initial Volume of Contaminated Groundwater Plumes at 24 Sites[1]



Note:
1 Plume volume presented here generally represents one pore volume of the contaminated plume prior to commencing groundwater cleanup activities at the site. Volume of the plume was reported by contractors or estimated during the preparation of the case study reports from contaminant isoconcentration and hydrogeologic data.

Exhibit 2-7 summarizes information on the observed and suspected presence of nonaqueous phase liquid (NAPL) at the sites either as light nonaqueous phase liquid (LNAPL), which generally floats on the water table, or dense nonaqueous phase liquid (DNAPL), which typically sinks through permeable media (including saturated materials) to an impermeable barrier. Of the 28 sites: NAPLs were observed or suspected to be present at 18; DNAPL only was observed or suspected at 12 sites; LNAPL only was observed or suspected at three sites; and both DNAPL and LNAPL was observed or suspected at three sites. As described in *Estimating Potential for Occurrence of DNAPL at Superfund Sites* [6], NAPL can be "suspected" at a site if its components are present in groundwater at greater than one percent of either their pure-phase solubility or effective solubility. For the case study sites, NAPL was considered "suspected" if at lease one component was present at greater than one percent of its pure-phase solubility.

Exhibit 2-7: Presence of NAPLs at 28 Sites

Site Name and Location	NAPL Observed or Suspected			
	DNAPL		LNAPL	
	Observed	Suspected[1]	Observed	Suspected[1]
Baird and McGuire, MA			●	
City Industries, FL				
Des Moines, IA		●		
Firestone, CA				
French, Ltd., TX	●			
Gold Coast, FL	●			
Intersil, CA				
JMT, NY		●		
Keefe, NH				
King of Prussia, NJ		●		
LaSalle, IL	●			
Libby, MT	●		●	
Moffett, CA		●		
MSWP, AR	●		●	
Mystery Bridge, WY				
Odessa I, TX				
Odessa IIS, TX				
Old Mill, OH				
SCRDI Dixiana, SC				
Site A, NY			●	
Sol Lynn, TX		●		
Solid State, MO		●		
Solvent Recovery Service, CT	●			
Sylvester/Gilson Road, NH			●	
U.S. Aviex, MI		●		
United Chrome, OR				
USCG Center, NC		●		
Western Processing, WA	●		●	
Number of Sites	7	8	6	0

Note:
[1] Suspected NAPL was identified in the case study reports when contaminants were present at more than one percent of their either their pure-phase solubility or effective solubility.

Exhibit 2-8 presents information about the hydrogeologic conditions at the 28 sites. The average hydraulic conductivity of the contaminated water-bearing layer(s) at the sites varied by more than six orders of magnitude (0.023 feet per day (ft/day) to 1,200 ft/day). At more than half of the sites, contamination was present in multiple water-bearing layers or aquifers. Seven of the sites exhibited vertical groundwater flow between aquifers, 13 sites were influenced by adjacent bodies of surface water, and eight sites were influenced by the presence of production wells (for example, municipal). Reported depths to the top of contaminated aquifers ranged from zero (at ground surface) to 45 ft below ground surface (bgs). Additional detail on the hydrogeologic conditions, such as aquifer type, lithology, and degree of heterogeneity at the sites can be found in the case studies.

Exhibit 2-8: Pertinent Hydrogeological Data at 28 Sites

Site Name and Location	Hydraulic Conductivity Range (ft/day)	Multiple Aquifer Contamination	Vertical GW Flow	Surface Water Influence	Production Wells in Area	Depth to Contaminated Aquifer (ft bgs)
Baird and McGuire, MA	3-45	Y	N	Y	N	10 - 15
City Industries, FL	6.39	Y	N	N	N	NR
Des Moines, IA	535	N	N	Y	Y	10 - 25
Firestone, CA	100-1200	Y	N	N	Y	NR
French, Ltd., TX	0.28-2.8	Y	N	Y	N	10 - 12
Gold Coast, FL	40	Y	N	Y	Y	5.0
Intersil, CA	370	N	Y	N	N	NR
JMT, NY	0.65-0.93	Y	N	N	N	10.0
Keefe, NH	42.5	N	N	N	N	NR
King Of Prussia, NJ	Variable	N	N	Y	N	15.0
LaSalle, IL	0.22	N	Y	N	N	3 - 5
Libby, MT	100-1000	Y	N	Y	Y	10 - 20
Moffett, CA	0.3-400	Y	Y	N	N	5.0
MSWP, AR	Variable	Y	N	N	N	NR
Mystery Bridge, WY	340	N	N	N	N	14 - 42
Odessa I, TX	1.6-5.1	Y	N	N	Y	30 - 45
Odessa IIS, TX	1.6-5.1	Y	N	N	Y	30 - 45
Old Mill, OH	0.22-1.25	N	N	Y	N	5.0
SCRDI Dixiana, SC	10	Y	N	N	N	14.0
Site A, NY	53.5	N	Y	Y	N	15 - 18
Sol Lynn, TX	0.14-25.5	Y	N	N	N	20 - 25
Solid State, MO	0.023-1.62	Y	Y	Y	Y	NR
Solvent Recovery Service, CT	0.023-300	Y	N	Y	N	NR
Sylvester/Gilson Road, NH	30-50	Y	Y	Y	N	NR
U.S. Aviex, MI	9.1-45.4	N	N	N	Y	20.0
United Chrome, OR	0.5-60	Y	Y	N	N	0 - 10
USCG Center, NC	11.3-25.5	N	N	Y	N	6.0
Western Processing, WA	1-100	Y	N	Y	N	5 - 10

Notes:
GW = Groundwater
NR = Not recorded in case studies

3.0 DESIGN AND OPERATION OF REMEDIAL SYSTEMS AT 28 CASE STUDY SITES

- Most of the sites used P&T alone; five of the sites used P&T in combination with *in situ* technologies
- Eighteen of the P&T systems at the sites used air stripping as aboveground treatment; carbon adsorption, metal removal, and biological treatment also were used to a lesser extent
- The volume of groundwater treated per year of operation at the P&T sites ranged from 1.7 million to 554 million gallons
- Optimization and modification efforts have been made to some extent at all of the sites

The design of the groundwater remediation systems at the 28 sites include: pump-and-treat (P&T) systems used alone as the remediation technology at 21 sites; *in situ* technologies (permeable reactive barriers [PRB] in these cases) used alone as the remediation technology at two sites, and *in situ* technologies, such as *in situ* bioremediation, air sparging, or PRBs, used in conjunction with or to replace P&T systems at five sites. Source controls were identified at 23 of the sites. Vertical containment barriers (VCB) were used at five of the sites to provide hydraulic control of contaminant plumes.

The technologies used at the 28 case study sites are described briefly below, followed by a detailed summary of the remedial system designs implemented at the case study sites.

3.1 Technology Descriptions

Pump-and-Treat

P&T involves extracting contaminated groundwater through recovery wells or trenches and treating the extracted groundwater by *ex situ* (aboveground) processes, such as air stripping, carbon adsorption, biological reactors, or chemical precipitation. Variables in the design of a typical P&T system include:

- The number and production rate of groundwater extraction points (determined by such factors as the extent of contamination and the productivity of the contaminated aquifer)
- The *ex situ* treatment processes employed (determined by such factors as system throughput and the contaminants that require remediation)
- The discharge location for treatment plant effluent (determined by such factors as location of the site and regulatory requirements)

Additional information about the fundamentals of P&T technology can be found in *Design Guidelines for Conventional Pump-and-Treat Systems* [1].

Air Sparging

Air sparging (AS) involves injecting a gas (usually air or oxygen) under pressure into the saturated zone to volatilize contaminants in groundwater. Volatilized vapors migrate into the vadose zone where they are extracted by vacuum, generally by a soil vapor extraction system. AS also is used to supplement P&T systems. For example, AS may be added to remediate specific portions of a contaminated plume that are not treated effectively by P&T alone or to accelerate cleanups. For the purpose of this report, the use of air to promote biodegradation (sometimes referred to as "biosparging") in saturated and unsaturated soils by increasing subsurface concentrations of oxygen is referred to as *in situ* bioremediation.

Permeable Reactive Barriers

A PRB, or treatment wall, consists of an in-ground trench that is backfilled with a reactive medium. The selection of the reactive medium is based on the targeted contaminants and the hydrogeologic setting of the site. Zero-valent iron is the most common medium used in PRBs to date. Examples of other reactive media include, microorganisms, zeolite, activated carbon, peat, phosphate, bentonite, limestone, and amorphous ferric oxide. The treatment processes that occur within the tremch are degradation, sorption, or precipitation of the contaminant. PRB systems may be configured as "funnel and gate" designs; in such configurations groundwater flow is routed by two or more impermeable walls through a permeable reactive zone.

PRBs may or may not be similar to P&T systems in both purpose and function. Like a P&T system, PRBs may be used to treat contaminated groundwater at the boundary of a site, or to restore the groundwater throughout a site. However, the volume of groundwater treated by a PRB at a site is typically much lower than it would be for a P&T system at the same site because PRBs treat only the groundwater that passes through the barrier, while P&T systems actively extract groundwater from an aquifer, usually at multiple locations throughout the plume.

In Situ Bioremediation

In situ bioremediation (ISB) involves microbial degradation of organic constituents through aerobic or anaerobic processes. *In situ* bioremediation includes processes by which nutrients (such as nitrogen and phosphorus), electron donors (such as methane for aerobic processes or methanol for anaerobic processes), or electron acceptors (such as oxygen for aerobic processes or ferric iron for anaerobic processes) are added to the groundwater to enhance the natural biodegradation processes. The addition of oxygen by biosparging is an example of such a process.

Source Controls

Source controls include such activities as excavation of soil at hot spots, *in situ* treatment of soil (for example, by soil vapor extraction), and installation of VCBs for control of NAPLs. Source controls are implemented to remove source materials or to isolate them from contact with groundwater.

Vertical Containment Barriers for Hydraulic Control

VCBs, such as slurry or sheet pile walls, also are used to hinder the migration of contaminated groundwater. VCBs are used in conjunction with groundwater extraction wells in an effort to gain hydraulic control over a contaminated groundwater plume.

3.2 Remedial System Designs

Exhibit 3-1 lists the remedial technologies used at the 28 subject sites. At most of the sites (26 of 28), P&T systems were used for groundwater remediation. At five of the P&T sites, *in situ* technologies were incorporated into the P&T approach. AS was incorporated at two sites, ISB at three sites, and PRBs at one site. At two sites, PRBs were used alone as the remedial technology. Source controls were used at most (24) of the sites, and VCBs were used for hydraulic control five sites.

Exhibit 3-1: Summary of Technologies Used at 28 Sites

Technology	Number of Sites
Total P&T Technologies	26
Total *In Situ* Technologies	7
P&T Only	21
P&T with *In Situ* Technology or Technologies	5
Air Sparging	*1*
In Situ Bioremediation	*2*
Air Sparging and In Situ Bioremediation	*1*
Permeable Reactive Barriers (replaced P&T)	*1*
In Situ Technology Only	2
Air Sparging	0
In Situ Bioremediation	0
Permeable Reactive Barriers	*2*
Vertical Containment Barriers for Hydraulic Control	5
Source Controls	24

Exhibit 3-2 identifies the specific remedial technology or technologies used at each of the sites. Extracted groundwater at the sites was treated using treatment systems varying from an individual *ex situ* technology to a complex series of different technologies. The *ex situ* treatment technologies included:

- Air stripping
- Carbon adsorption
- Filtration
- Electrochemical removal of metals
- Oil/water separation
- Chemical or ultraviolet oxidation
- Biological degradation
- Neutralization
- Equalization

Vapor-phase treatment of off-gases from the *ex situ* technologies was employed at eight of the sites. At those sites, vapor-phase incineration, carbon adsorption, filtration, or thermal oxidation were used either individually or in series.

Exhibit 3-2: Remedial Technologies Used at 28 Sites

Site Name and Location	Remediation Technology										Source Control(s) Implemented
	P&T (with *ex situ* treatment)						AS	ISB	PRB	VCB	
	OWS	STRIP	GAC	METAL	BIO	Other					
Baird and McGuire, MA		●	●	●		Filtration					Concurrent excavation
City Industries, FL		●				Equalization					Prior excavation
Des Moines, IA		●									Prior excavation
Firestone, CA	●	●	●			Filtration					Prior excavation
French, Ltd., TX			●	●	●	Neutralization; addition of nutrients and oxygen		●		●	Prior *in situ* bioremediation of soil and sludges
Gold Coast, FL		●					●				NA
Intersil, CA		●							●		Prior excavation
JMT, NY		●									Prior excavation
Keefe, NH		●		●						●	Prior excavation
King of Prussia, NJ			●	●		Equalization; clarification; filtration					Prior soil washing
LaSalle, IL	●	●	●								Prior excavation
Libby, MT	●				●			●			Prior excavation
Moffett, CA									●		NA
MSWP, AR	●		●			Filtration					Prior excavation
Mystery Bridge, WY		●									Prior excavation/SVE
Odessa I, TX				●		Filtration					NA
Odessa IIS, TX				●		Filtration					Prior excavation
Old Mill, OH		●	●								Prior excavation
SCRDI Dixiana, SC		●		●							Prior excavation
Site A, NY		●				Settling; filtration; addition of nutrients; pH adjustment of effluent	●	●			Prior excavation
Sol Lynn, TX		●	●	●		pH adjustment					Prior excavation
Solid State, MO		●									Prior excavation
Solvent Recovery Service, CT			●	●		Oxidation; filtration; pH adjustment				●	Prior excavation
Sylvester/Gilson Road, NH		●		●	●					●	Prior and concurrent capping/slurry wall/ excavation/SVE
U.S. Aviex, MI		●									NA
United Chrome, OR				●							Prior excavation
USCG Center, NC									●		Prior excavation
Western Processing, WA		●	●			Oxidation; filtration				●	NA
Total Sites	4	18	10	11	3		2	3	3	5	

Notes:

OWS	=	Oil/water separation	AS	=	Air sparging
STRIP	=	Air stripping	ISB	=	*In Situ* bioremediation
GAC	=	Granular activated carbon adsorption	PRB	=	Permeable reactive barrier
METAL	=	Physical or chemical removal of metal	VCB	=	Vertical containment barrier
BIO	=	Biological treatment	NA	=	Not Available

Exhibit 3-3 identifies the extraction system design for each of the P&T sites. Groundwater extraction designs at the 26 P&T sites varied in magnitude from one production well (*JMT*) to several wells combined with trenches (*MSWP* and *Old Mill*) and to 210 vacuum wellpoints (*Western Processing*). Pumping rates for the P&T systems ranged from 3 gallons per minute (*Old Mill*) to more than 1,000 gallons per minute (*Des Moines*).

Exhibit 3-3: Pump-and-Treat System Designs at 26 Sites

	Number of Wells		Number of Trenches		Pumping Rate	Number Of Wells/ Trenches (by Location)		Treated Groundwater Discharge		
Site Name, Location	Extract	Inject	Extract	Inject	Average gpm	On-site	Off-site	Re-injected	Surface Water	POTW
Baird and McGuire, MA	6	0	0	0	60	6	0	●		
City Industries, FL	13	0	0	0	105	13	0	●		
Des Moines, IA	7	0	0	0	1041	7	0		●	
Firestone, CA	25	0	0	0	484	15	10			●
French, Ltd., TX	109	59	0	0	189	NR	NR	●		
Gold Coast, FL	5	3	0	0	44	5	0	●		
Intersil, CA	3	0	0	0	8	4	0		●	
JMT, NY	1	0	0	0	11.2	1	0	NR	NR	NR
Keefe, NH	5	0	1	0	23.4	1	5		●	
King of Prussia, NJ	11	0	0	0	200	4	7		●	
LaSalle, IL	0	0	3	0	17	3	0			●
Libby, MT	5	11	0	0	6.6	5	0	●	●	
MSWP, AR	15	0	8	0	24	10	5		●	
Mystery Bridge, WY	3	0	0	0	103	3	0	●		
Odessa I, TX	6	6	0	0	60	NR	NR	●		
Odessa IIS, TX	10	9	0	0	58.5	NR	NR	●		
Old Mill, OH	3	0	5	0	3.1	NR	NR	●		
SCRDI Dixiana, SC	15	0	1	0	40	8	12	●		
Site A, NY	5	0	0	1	18	5	0		●	
Sol Lynn, TX	12	14	0	0	8	NR	NR	●		●
Solid State, MO	7	0	0	0	34	4	3		●	
Solvent Recovery Service, CT	12	0	0	0	20	6	6	●		
Sylvester/Gilson Road, NH	14	0	0	7	265	14	0	●		
U.S. Aviex, MI	5	0	0	0	220	1	4		●	
United Chrome, OR	30	0	0	0	242	NR	NR		●	
Western Processing, WA	210	0	0	1	230	210	3		●	
Minimum	**0**	**0**	**0**	**0**	**3.1**	**1**	**0**			
Maximum	**210**	**59**	**8**	**7**	**1041**	**210**	**12**			
Average	**21**	**4**	**0.7**	**0.4**	**140**	**16**	**3**			
Median	**7**	**0**	**0**	**0**	**51**	**5**	**0**			

Notes:
NR = Not reported

Exhibit 3-3 shows that treated groundwater was reinjected into the aquifer (11 sites), discharged to an adjacent surface water by a permitted outfall (10 sites), discharged to a publicly owned treatment works (POTW) (2 sites), or discharged using a combination of these methods (2 sites). Exhibit 3-4 describes the remedial systems at the seven case study sites where *in situ* technologies were used.

Exhibit 3-4: Designs of *In Situ* Treatment Systems at Seven Sites

Site Name and Location	*In Situ* Technology(ies) Used	Design of *In Situ* Treatment System
French, Ltd., TX	ISB	P&T system augmented with ISB. ISB system consisted of the reinjection of treated groundwater into the contaminated aquifer. The treated groundwater was oxygenated and amended with nitrogen and phosphorus before reinjection.
Gold Coast, FL	AS	AS used only at end of cleanup to mitigate a small area of localized contamination.
Intersil, CA	PRB	Original design was a P&T system, which was turned off in 1995 after PRB was installed. PRB system consisted of two parallel slurry walls 300 and 235 feet long and 13 feet deep used to funnel groundwater through a 40-foot-wide, 4-foot-thick permeable wall of granular iron.
Libby, MT	ISB	P&T system complemented with ISB. ISB system consisted of the reinjection of treated groundwater into the contaminated aquifer. Treated groundwater was aerated and amended with nitrogen and phosphorus in the treatment plant after removal of NAPL and before it flowed through a series of fixed-film bioreactors.
Moffett, CA	PRB	PRB consisted of an impermeable "funnel" composed of two 20-foot-long sheet pile walls. Reactive zone consisted of 6-foot-thick, 10-foot-wide, and 18-foot-high (beginning 5 feet bgs) zone of granular iron. The reactive zone was located between two zones of pea gravel, each two feet thick.
Site A, NY	AS and ISB	P&T system in conjunction with AS and ISB. AS system consisted of air injection through 44 sparging wells at points approximately 10 feet below the water table, with vapor collection through 20 soil vapor extraction wells (16 vertical and 4 horizontal). ISB system consisted of the reinjection of treated groundwater into the contaminated aquifer. The treated groundwater was amended with nitrogen and phosphorus before it was discharged to the reinjection trench.
USCG Center, NC	PRB	PRB consisted of a 2-foot-thick and 152-foot-long zone of approximately 450 tons of granular zero-valent iron keyed into an underlying low conductivity layer at approximately 22 feet bgs.

3.3 System Operation

Exhibit 3-5 presents data available on the operation of the remedial systems, including the volume of groundwater treated and the percent of time the systems were operational. The volume of groundwater treated per year of operation for the P&T systems ranged from 1.7 million gallons (*Old Mill*) to 554 million gallons *(Des Moines)*. Estimated throughput per year for the PRB sites ranged from 200,000 gallons (*Moffett*) to 2.6 million gallons (*USCG Center*).

Exhibit 3-5: Operation of Remedial Systems at 28 Sites

Site Name and Location	Volume of GW Extracted (million gallons)[1]		Percent of Time Operational (%)
	Total	Per Year	
Baird and McGuire, MA	80	21	93
City Industries, FL	151.7	50	90
Des Moines, IA	4900	554	95
Firestone, CA	1800	266	97
French, Ltd., TX	306	76	90
Gold Coast, FL	80	22	95
Intersil (P&T), CA[3]	36	5.0	98
Intersil (PRB), CA[2,3]	2	1.1	100
JMT, NY	50.1	5.2	90
Keefe, NH	46	11	97
King of Prussia, NJ	151.5	57	76
LaSalle, IL	23	5.2	75
Libby, MT	15.1	2.9	89
Moffett (PRB), CA[2]	0.284	0.2	100
MSWP, AR	100.6	12	NR
Mystery Bridge, WY	192.8	54	100
Odessa I, TX	125	30	95
Odessa IIS, TX	121	30	95
Old Mill, OH	13	1.7	99
SCRDI Dixiana, SC	20.6	4.5	89
Site A, NY	8.4	6.7	75
Sol Lynn, TX	13	4.3	69
Solid State, MO	257	62	95
Solvent Recovery Service, CT	32.5	11	100
Sylvester/Gilson Road, NH	1200	126	88
U.S. Aviex, MI	329	96	95
United Chrome, OR	62	7.2	99
USCG Center (PRB), NC[2]	2.6	2.6	100
Western Processing, WA	974	119	97
Minimum	0.284	0.2	69
Maximum	4900	554	100
Average	382.5	57	92
Median	80	12	95

Notes:
1 At most of the sites, groundwater cleanups are in progress; therefore the values shown represent a portion of the total volume treated. Data presented here generally are cumulative as of late 1997 or early 1998.
2 The volume of groundwater for PRB sites is equal to the volume of groundwater treated through the wall at the site.
3 At the Intersil site, groundwater cleanup began with a P&T system; later a PRB was used. The two phases were treated above as separate sites.
NR = Not reported

The percent of time that the remedial systems were operational at the sites ranged from 69 to 100 percent. Downtime reportedly was required for routine maintenance (such as changing carbon, cleaning air stripper media, and backwashing filters) and issues specific to particular sites, including:

- Iron corrosion and clogging of extraction wells (*Baird and McGuire, Des Moines, Odessa I, Odessa IIS, Mystery Bridge,* and *Solvent Recovery Services*)
- Freezing or fouling of air stripper media (*Solid State* and *City Industries*)
- System modifications (*Keefe, Solid State, Site A, MSWP,* and *Sylvester/Gilson Road*)
- Equipment failures (*Libby, French, Ltd.,* and *King of Prussia*)
- Brownouts (*Keefe*)

3.4 System Optimization and Modifications

Optimization and modification efforts that have been undertaken at the case study sites include remedy refinement, pre-design modeling and testing, and system modifications. Exhibit 3-6 summarizes the types of optimization and modification efforts reported for the case study sites; these are generally classified as pre-design and post-design efforts. Pre-design efforts at the case study sites typically consisted of interim designs or systems (used at 13 sites) and groundwater modeling (used at 11 sites). Post-design efforts consisted of optimization modeling (used at 13 sites), modifications of the groundwater extraction systems (used at twenty of the sites), and modifications to the groundwater treatment systems (used at 15 sites). Exhibit 3-7 lists the specific efforts made at each of the 28 sites.

At the time the case study reports were prepared, some of the sites at which remediation was ongoing had identified plans for future system modifications. The following examples illustrate these types of plans:

- At *U.S. Aviex*, further site characterization is needed and the remediation system may require expansion.
- At *City Industries*, concentrations of contaminants in extracted groundwater may be low enough to allow discharge directly to the POTW without prior treatment.
- At *Sol Lynn*, the system was shut down when extraction well pipes leaked and fouled, and the extraction system had lost containment. Currently, the site is being reevaluated to identify alternative remedial plans to address the issues with the extraction system.

Exhibit 3-6: Types of Optimization and Modification Efforts at 28 Sites[1]

Pre-Design	Pre- or Post-Design	Post-Design			
		Optimization/Modifications of Extraction System		Optimization/Modifications of Treatment System	
Interim Design or System	Groundwater/ Optimization Modeling	Modifications	Purpose/ Objective	Modifications	Purpose/ Objective
• Pilot-scale system	• MODFLOW	• Add extraction points	• Increase extraction rate/ contain plume	• Increase or reduce equipment capacity	• Make capacity of treatment plant match that of extraction system
• Demonstration system	• MT3D	• Abandon extraction points	• Respond to reduction in extent of contamination	• Add chemical enhancements to system	• Halt fouling of equipment; enhance removal of solids; enhance biodegradation of contaminants
• Staged approach to construction	• Quickflow	• Resize extraction pumps	• Increase efficiency of system		
• Treatability testing	• Randomwalk	• Adjust pumping rates	• Increase efficiency of system	• • Add or replace with *in situ* technologies	• Increase performance or cost-effectiveness of the system
• Interim system to contain plume while full system is designed	• Biotrans	• Change type of pump	• Reduce shearing or aeration of extracted groundwater	• Upgrade process equipment	• Increase performance or cost-effectiveness of the system
	• (for most sites, the type of modeling was not specified)	• Modify extraction system design	• Increase efficiency of system or respond to changes in remedial goals	• Add process units to treatment train	• Address unexpected contaminants or increase performance or efficiency of system
		• Use alternate remediation method	• Allow use of more cost-effective method (for example, AS or natural attenuation)	• Automate treatment system operation	• Allow remote monitoring; reduce O&M cost
		• Implement or expand source controls	• Respond to new source or increase efficiency in treating existing source areas	• Discontinue treatment	• When discharge of untreated water is permitted
		• Reduce performance monitoring	• Reduce O&M costs	• Reduce compliance monitoring	• Reduce O&M costs

Notes:
1 Because the focus of the case studies was not on optimization, the types of optimization efforts listed in this table are not necessarily a comprehensive list of optimization efforts performed at all of the case study sites.

Exhibit 3-7: System Optimization and Modification Efforts Conducted at 28 Sites[1]

Site Name	Pre-Design		Post-Design				
	Interim Design	Groundwater Modeling System	Optimization Modeling	Modifications to Extraction System		Modifications to Treatment System	
				Modification	Reason	Modification	Reason
Baird and McGuire SF Site	None identified	Yes; provided no details	Yes; provided no details	Resized extraction pumps	Increase pumping rate to meet design criteria	Enlarged sludge thickener/replaced bioreactor with air stripper	Enable treatment plant unable to meet design flowrate/maintain biomass at design flowrates and contaminant concentrations
City Industries SF Site	None identified	None identified	Examined varying pumping rates	Increased pumping from leading edge of plume and decreased pumping from upgradient wells	Maximize pumping zones of influence	None identified	Not applicable
Des Moines TCE SF Site	None identified	Two-dimensional MODFLOW	None identified	None identified	Not applicable	AS media changed from spherical to chandelier type/ anti-corrosion and biofouling agents added to AS	Address iron corrosion and biofouling of AS media
Former Firestone Facility SF Site	None identified	Yes; provided no details	Yes; provided no details	Installed 10 additional wells off-site/ adjusted pumping rates/ increased overall pumping rate for a 2 week period	Prevent migration of contaminated plume into intermediate zones	None identified	Not applicable
Former Intersil, Inc. Site	One extraction well w/air stripper to start	Yes; provided no details	Yes; provided no details	None identified	Not applicable	P&T system upgraded/switched from P&T to PRB in 1995	Reduce treatment costs and allow for transfer of the property

Table Continued...

Notes:

[1] Because the focus of the case studies was not on optimization, the optimization efforts listed in this table are not necessarily a comprehensive list of optimization efforts performed at the case study sites.

Exhibit 3-7: System Optimization and Modification Efforts Conducted at 28 Sites[1]

Site Name	Pre-Design		Post-Design				
	Interim Design	Groundwater Modeling System	Optimization Modeling	Modifications to Extraction System		Modifications to Treatment System	
				Modification	Reason	Modification	Reason
French, Ltd. SF Site	Staged approach	None identified	MODFLOW and Biotrans	None identified	Not applicable	Added second sheet-pile wall around DNAPL/ shut system down in 12/95	Address DNAPL detected/ continue remediation of the site via natural attenuation, as specified in the site ROD
Gold Coast SF Site	None identified	None identified	None identified	Enlarged two extraction wells/shut down system for four months/conducted air sparging in "source" areas/added peroxide to wells for a period, with no effect	Increase extraction rate/ increase amount of TCE and PCE desorbing from soil	None identified	Not applicable
JMT Facility RCRA Site (formerly Black & Decker)	Pilot test	None identified	None identified	Conducted full-scale rehabilitation of extraction well/ installed an electrical and piping box at extraction well	Unclog well/minimize time to perform routine maintenance checks on system	Constructed enclosure around the treatment system	Consolidate system operation in one building
Keefe Environmental Services SF Site	None identified	Yes; provided no details	Yes; provided no details	Constructed two replacement extraction wells	Optimize system after reevaluation because cleanup goals were not being met	None identified	Not applicable
King of Prussia Technical Corporation SF Site	None identified	MODFLOW and MT3D	Ongoing, using MODFLOW and MT3D	None identified	Not applicable	None identified	Not applicable
LaSalle Electrical SF Site	None identified	None identified	None identified	None - original design considered adequate	Not applicable	None - original design considered adequate	Not applicable

Table Continued...

Notes:
1 Because the focus of the case studies was not on optimization, the optimization efforts listed in this table are not necessarily a comprehensive list of optimization efforts performed at the case study sites.

Exhibit 3-7: System Optimization and Modification Efforts Conducted at 28 Sites[1]

Site Name	Pre-Design		Post-Design				
	Interim Design	Groundwater Modeling System	Optimization Modeling	Modifications to Extraction System		Modifications to Treatment System	
				Modification	Reason	Modification	Reason
Libby Groundwater SF Site	Pilot test and demonstration for *in situ* bioremediation	None identified	None identified	Tested and converted to lower-shear pumps/ four extraction wells abandoned, and one new well constructed	Increase effectiveness of OWS/address decrease in areal extent of contamination	Peroxide system for aeration of ISB source water replaced with bubbleless system	Minimize treatment costs
Mid-South Wood Products SF Site	1985-89 french drains	None identified	None identified	Removed five extraction wells/ continuously adjusted pumping schedule of extraction wells	No contaminants detected in the five wells/ schedule adjusted according to concentration results	Added carbon treatment system for one year	Allow for use of treated groundwater in production facility
Moffett Federal Airfield	Currently in pilot-test stage	None identified	None identified	None identified	Not applicable	None identified	Not applicable
Mystery Bridge at Highway 20 SF Site, Dow/DSI Facility	None identified	Quickflow	None identified	None identified	Not applicable	None identified	Not applicable
Odessa Chromium I SF Site	30-day pilot study	Randomwalk and Geoflow	Yes; provided no details	Added three injection wells/converted two monitoring wells to recovery wells	Achieve higher injection rate/attempt to fully capture plume	Added chamber to reaction tank/ added backwash unit for filter	Precipitate iron before stripping and filtering
Odessa Chromium IIS SF Site	30-day pilot study	Randomwalk and Geoflow	Yes; provided no details	Added two injection wells/installed recovery well	Achieve higher injection rate/expedite cleaning of source area	Added chamber to reaction tank/ added a backwash unit	Precipitate iron before stripping and filtering
Old Mill SF Site	None identified	None identified	None identified	Added three collection trenches	Address new areas of contamination discovered	Replaced two carbon canisters with one	Eliminate over design

Table Continued...

Notes:
[1] Because the focus of the case studies was not on optimization, the optimization efforts listed in this table are not necessarily a comprehensive list of optimization efforts performed at the case study sites.

Exhibit 3-7: System Optimization and Modification Efforts Conducted at 28 Sites[1]

Site Name	Pre-Design		Post-Design				
	Interim Design	Groundwater Modeling System	Optimization Modeling	Modifications to Extraction System		Modifications to Treatment System	
				Modification	Reason	Modification	Reason
SCRDI Dixiana SF Site	1992-4 EPA system/20 wells at 4 gpm	None identified	Quickflow	Added collection trench/ reduced extraction wells by five (15 remain in operation)	Collect contaminated groundwater from shallow zone/achieve more efficient hydraulic control	Replaced tower air stripper with shallow-tray stripper	Tower air stripper was struck by lightning
Site A (Confidential SF Site)	Bioremediation study	None identified	None identified	Expanded system by adding more sparging wells	Address additional contamination discovered during demolition activities	None identified	Not applicable
Sol Lynn/Industrial Transformers SF Site	None identified	MODFLOW	MODFLOW	Adjusted pumping strategy because of additional contamination in the silty aquifer identified	Prevent cross-contamination of zones and prevent further migration of contaminants	None identified	Not applicable
Solid State Circuits SF Site	None identified	None identified	None identified	Added three wells off site	Contain plume	Electronically linked air stripper blower to transfer pumps so blower would shut off when not pumping	Prevent freezing problems with blowers
Solvent Recovery Services of New England, Inc. SF Site	None identified	None identified	None identified	None identified	Not applicable	None identified	Not applicable
Sylvester/Gilson Road SF Site	4-well GW circulation	None identified	MODFLOW	Added six extraction wells	Address hot spots	None identified	Not applicable

Table Continued...

Notes:
1 Because the focus of the case studies was not on optimization, the optimization efforts listed in this table are not necessarily a comprehensive list of optimization efforts performed at the case study sites.

Exhibit 3-7: System Optimization and Modification Efforts Conducted at 28 Sites[1]

Site Name	Pre-Design: Interim Design	Pre-Design: Groundwater Modeling System	Post-Design: Optimization Modeling	Modifications to Extraction System: Modification	Modifications to Extraction System: Reason	Modifications to Treatment System: Modification	Modifications to Treatment System: Reason
U.S. Aviex SF Site	1983-93 interim remedial measure	MODFLOW and Randomwalk	MODFLOW and Randomwalk	Adjusted pumping rates for each well continuously	Optimize system on the basis of concentration data for each well	Added pH adjustment	Reduce scaling of equipment and discharge piping
U.S. Coast Guard Support Center	1994 pilot study	None identified	None identified	None identified	Not applicable	None identified	Not applicable
United Chrome SF Site	None identified	None identified	None identified	Turned off some extraction wells/ flushed some areas	Stop treatment in areas with contaminant concentrations below cleanup levels/solubilize contaminants in areas of higher contamination flushed	Switched to sending untreated water to POTW/ injected deep aquifer water into upper aquifer	Minimize treatment costs/ discontinue rapid dewatering of upper aquifer
Western Processing SF Site	None identified	None identified	None identified	Discontinued operation of 210 shallow well points/installed deep wells	Address change in remedial goal from remediation to containment	Added metals precipitation to treatment system/ replaced carbon type	Address severe fouling of air stripping media/ minimize frequency of carbon changouts required

Notes:

[1] Because the focus of the case studies was not on optimization, the optimization efforts listed in this table are not necessarily a comprehensive list of optimization efforts performed at the case study sites.

4.0 PERFORMANCE OF REMEDIAL SYSTEMS AT 28 CASE STUDY SITES

This section discusses the performance of the remedial systems used at the 28 sites in terms of the remedial goals set for the sites and progress made toward achieving those goals.

- Two of 28 sites have met all aquifer restoration goals
- Most sites have made progress toward meeting remedial goals, including reducing or eliminating a hot spot within a plume, reducing the mass of contaminants within a plume, and reducing concentrations of contaminants within a plume

4.1 Remedial Goals

Remedial goals for the containment and mitigation of contamination have been established at all the case study sites. The remedial goals for the sites included the restoration of all groundwater beneath the site and any off-site groundwater that may have been affected by the site, as well as the containment of on-site contamination, allowing off-site contamination to attenuate naturally. It should be noted that all of the sites selected for case studies were chosen because they had established aquifer cleanup goals and not just containment only goals, although goals at one site (*Western Processing)* have been changed to containment only since the case studies were prepared. In addition, performance goals for the treatment systems, such as requirements related to water discharge of water and air emissions, were established for a number of the sites. Exhibit 4-1 identifies the goals established for each site and whether the goals have been achieved.

Cleanup goals for the sites were established based on one or more of the following factors:

- Maximum contaminant levels (MCL)
- Primary drinking water standards
- Risk-based cleanup levels
- Approved alternative concentration limits (ACL)
- Optional cleanup levels for a non-time-constrained removal action
- Concentrations of contaminants in adjacent surface waters

For two-thirds of the sites, the aquifer goals established were based on MCLs.

Goals for the containment of contaminated groundwater were established for 25 of the 28 sites. The manner of containment required at each site varied but typically consisted of containment of the contaminated groundwater on-site or halting of the continued migration of an existing off-site plume.

Limits on air emissions were identified for three of the sites (*JMT, LaSalle, and Libby*). During preparation of the case study reports, EPA did not focus on whether air emission limits were established; therefore, it is possible that the reports did not identify limits at some of the other sites.

Exhibit 4-1: Summary of System Performance for 28 Sites

		Remedial Goals			Performance Goals		Contaminant Mass Removed[1]
Site Name and Location	Remedial Technology	Restore Aquifer	Contain Plume	Cleanup Level Basis	Air Emission	Water Discharge	Total Pounds
Baird and McGuire, MA	P&T	○	○	MCLs, surface water	NR	NR	2,100
City Industries, FL	P&T	○	✪	MCLs	NR	✪	2,700
Des Moines, IA	P&T	○	✪	MCLs	NR	NR	30,000
Firestone, CA[2]	**P&T**	✪	✪	MCLs, drinking water criteria, risk-based	**NR**	✪	**500**
French, Ltd., TX	P&T, ISB	○	✪	risk-based	NR	NR	510,000
Gold Coast, FL[2]	**P&T, AS**	✪	✪	MCLs, drinking water	**NR**	✪	**2,000**
Intersil, CA	P&T, AS, PRB	○	✪	MCLs	NR	✪	120 (P&T); 15 (PRB)
JMT, NY	P&T	○	✪	MCLs	✪	✪	840
Keefe, NH	P&T	○	✪	ACLs	NR	✪	68
King of Prussia, NJ	P&T	○	✪	MCLs	NR	✪	5,400
LaSalle, IL	P&T	○	NE	drinking water	✪	NR	130
Libby, MT	P&T, ISB	○	NE	MCLs, risk-based	✪	NR	37,000
Moffett, CA	PRB	○	✪	drinking water	NR	NE	NR
MSWP, AR	P&T	○	✪	MCLs, risk-based	NR	○	800
Mystery Bridge, WY	P&T	○	NE	MCLs	NR	✪	21
Odessa I, TX	P&T	○	✪	MCLs	NR	✪	1,100
Odessa II, TX	P&T	○	✪	MCLs	NR	✪	130
Old Mill, OH	P&T	○	✪	risk-based	NR	✪	120
SCRDI Dixiana, SC	P&T	○	✪	MCLs	NR	✪	7
Site A, NY	P&T, AS, ISB	○	✪	MCLs	NR	NR	5,300
Sol Lynn, TX	P&T	○	○	MCLs	NR	✪	5,000
Solid State, MO	P&T	○	✪	MCLs	NR	NR	2,700
Solvent Recovery Service, CT	P&T	○	✪	To be set	NR	✪	4,300
Sylvester/Gilson Road, NH	P&T	○	✪	ACLs	NR	✪	430,000
U.S. Aviex, MI	P&T	○	○	MCLs	NR	✪	660
United Chrome, OR	P&T	○	✪	MCLs, risk-based	NR	✪	31,000
USCG Center, NC	PRB	○	○	drinking water	NR	NE	NR
Western Processing, WA	P&T	○	✪	MCLs	NR	✪	100,000

Minimum	7
Maximum	**510,000**
Average	**43,000**
Median	**2,000**

Notes:

○	Goal established but not met
✪	Goal established and met
NR	Goal established, but performance not reported
NE	Goal not established

1 For sites at which groundwater cleanups are ongoing, the total mass of contaminant removed represents the performance reported as of late 1997 or early 1998. Contaminant mass removals were calculated based on various types of mass balances around the site treatment system, not based on groundwater monitoring data. Insufficient data were available to calculate a removal of contaminant mass by *in situ* bioremediation; for those sites at which used *in situ* bioremediation was used, the contaminant mass removed may be greater than shown here.

2 Firestone and Gold Coast - remediation has been completed at these two sites.

Contaminant Mass Removed

Exhibit 4-1 presents the contaminant mass removed for the case study sites. For 26 of the sites, the mass of contaminant removed by the remediation systems was reported or could be calculated from reported data. When concentration and throughput data for the treatment system were available, these data were used to calculate the mass of the contaminant removed. Contaminant mass removals calculated based on groundwater monitoring results were not available. Total mass of contaminant removed ranged from seven pounds (*SCRDI Dixiana*) to 510,000 pounds (*French, Ltd.*), with an average of approximately 43,000 pounds and a median of approximately 2,000 pounds. For almost one-third of the sites, contaminant mass removed ranged from 1,000 to 10,000 pounds per site.

Because mass removal rates are dependent on many factors, including the extent and concentration of the contamination, contaminant properties, and the volume of groundwater treated, they generally are not used to evaluate the achievement of remedial goals. The variability is demonstrated in Exhibit 4-2 which shows the average mass of contaminant removed per year and per 1,000 gallons of water treated at each site. Contaminant mass removed per year for the 26 sites varies from approximately two pounds to more than 100,000 pounds, and from approximately 0.0001 pounds per 1,000 gallons treated to three pounds per 1,000 gallons treated. Sites with relatively higher mass removal rates per year do not consistently show relatively higher mass removal rates per 1,000 gallons treated. This may be due in part to differences in the concentration of contamination in the extracted groundwater. In addition, while not completed for this report (due to a lack of available data), a comparison of mass removal rates at a site over time can generally be useful in evaluating changes in system performance, for example, in identifying when removal rates are approaching asymptotic values (see the case studies for *Western Processing* and *Firestone*).

Reduction in Concentrations of Contaminants

Exhibit 4-3 presents the average reductions in concentrations of contaminants at the case study sites, sorted by the number of years which the remediation system was in operation (for this report, the number of years of performance data available). Average concentrations of contaminants could be calculated on the basis of available data for 17 of the 28 case study sites. For several of the sites, average concentrations of contaminations were reported only for a group of contaminants, and several others reported average concentrations of contaminants by individual contaminant. In addition, three of the sites (*United Chrome, Odessa II,* and *French Ltd.*) reported individual average concentrations of contaminants for more than one aquifer.

Exhibit 4-2: Unit Contaminant Mass Removed at 26 Sites

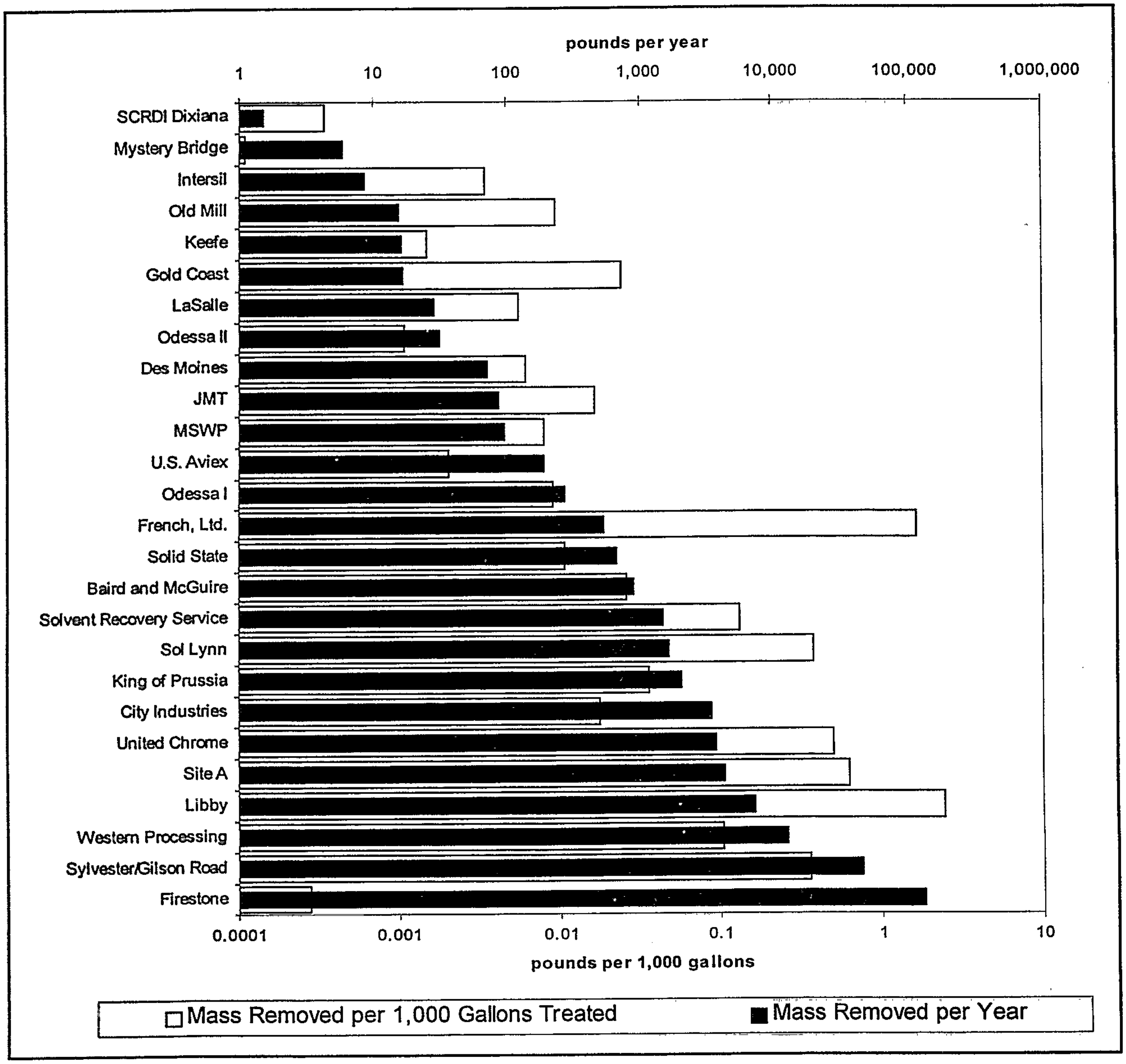


Exhibit 4-3: Summary of Average Contaminant Concentration Reduction at 17 Sites

Site Name and Location	Basis[1]		Average Contaminant Concentration (µg/L)[2]		Years of Data	Percent Reduction[3]
	Contaminant(s)	Zone[1]	Start	End		
Intersil, CA	VOCs (4 contaminants)		1,609	31	11.1	98
Des Moines, IA	VOCs (3 contaminants)		87	10	9	89
	TCE		45	3	9	93
JMT, NY	VOCs (4 contaminants)		950	30	8.6	97
	TCE		450	7	8.6	98
United Chrome, OR	Chromium	Shallow Aquifer	1,923,000	18,000	8.6	99
	Chromium	Deep Aquifer	1,400	110	8.6	92
MSWP, AR[4]	Metals/VOCs (4 contaminants)		140	90	7.1	36
	As		3	4	7.1	-33
	PCP		22	11	7.1	50
	Cr		30	5	7.1	83
	Total PAHs		35	23	7.1	34
Odessa I, TX	Chromium		980	540	5	45
Gold Coast, FL	PCE		176	1	4.9	99
	TCE		88	1	4.9	99
Odessa II, TX[4]	Chromium	Perched Aquifer	180	190	4.8	-6
	Chromium	Trinity Aquifer	400	50	4.8	88
LaSalle, IL[4]	PCBs/ VOCs	Shallow Aquifer	400	570	4.2	-43
French, Ltd., TX	1,2-DCA	S1 Aquifer/INT Aquifer	256/ 917	0.8/ 1	3.9	>99
	Vinyl chloride	S1 Aquifer/INT Aquifer	129/ 420	1.2/ 1	3.9	>99
	Benzene	S1 Aquifer/INT Aquifer	516/ 640	0.6/ 2	3.9	>99
U.S. Aviex, MI	1,1,1-TCA		107	40	3.6	63
	VOCs (10 contaminants)		158	67	3.6	58
Keefe, NH	VOCs (5 contaminants)		80	18	3.5	78
LaSalle, IL	PCBs/ VOCs	Deep Aquifer	100	6	3.2	94
City Industries, FL	VOCs and SVOCs (16 contaminants)		3,121	444	3	86
King of Prussia, NJ	Metals (6 contaminants)		3,500	1,500	2.6	57
	VOCs (9 contaminants)		4,500	4,000	2.6	11
Baird and McGuire, MA	VOCs (specific contaminants not identified)		500	420	1	16
	SVOCs (specific contaminants not identified)		1,000	520	1	48
Site A, NY	BTEX		160	26	1	84

Notes:

1 Data on average concentrations were reported for 17 of the 28 case study sites; for those sites, data are shown here by contaminant(s) and zone; zones are noted only for those sites at which concentrations of contaminants were reported for more than one aquifer.

2 Average concentrations of contaminants are based on a reported geometric mean of all data, as presented in the case study reports; for sites with ongoing cleanups, average concentrations of contaminants shown at "end" time represent the concentrations reported as of the date that data were available, typically late 1997 or early 1998.

3 Percent reduction was calculated as the difference between average concentrations of contaminants at start and end points, divided by the average concentration at the start.

4 Negative percent contaminant reductions were measured at three sites. These anomalies are discussed in the case studies for the sites.

4.2 Progress Toward Goals

Exhibit 4-4 lists the number of sites that have met specific remedial and system performance goals.

Exhibit 4-4: System Performance Summary

Goal	Number of Sites with Specified Goals [1]	Number of Sites Meeting Specified Goals
Remedial Goals		
Aquifer Restoration	28	2
Containment	25	22
System Performance Goals		
Air emissions [2]	3	3
Discharge of water	19	18

Notes:
[1] Goals for each site are specified in the case study reports.
[2] Air emission goals were specifically identified for only three of the case study sites.

Gold Coast and *Firestone* are the two case study sites for which all remedial goals have been met, as described briefly below.

- *Gold Coast* was a spent oil and solvent recovery facility that operated from 1970 to 1982. In the 1980s, groundwater was determined to be contaminated with chlorinated and nonchlorinated VOCs at levels as high as 100 milligrams per liter. A P&T system consisting of five extraction wells (pumping at a total of approximately 100 gpm) and two air stripping towers was put on line in 1990. By the end of 1994, concentrations of groundwater contaminants were reduced to levels lower than cleanup standards, with the exception of one source area. A limited air sparging effort was able to reduce the contaminant levels in that area to levels lower than cleanup standards by 1995. The site is located over a porous limestone aquifer, which facilitated groundwater pumping, and the use of source controls and in situ technology were identified as key factors in the success of the cleanup.

- The *Firestone* facility operated as a tire manufacturing plant from 1963 until 1980. In 1984, a 2.5-mile-long contaminated groundwater plume that contained chlorinated solvents was identified. The primary target contaminant in the plume was 1,1-DCE. A P&T system consisting of 35 extraction wells and *ex situ* air stripping and carbon adsorption was put on line in 1986. By 1987, the contaminated plume was contained and by 1992 the concentrations of 1,1-DCE in the plume had been reduced to levels lower than the cleanup goals and the system was shut down. During the operation of the groundwater extraction system, the site operators frequently adjusted it to maintain maximum concentration of contaminant at the treatment plant influent. That factor was identified as a key one in the success of the cleanup.

In addition to the two sites listed above at which the specified aquifer cleanup goals have been met, progress has been made toward meeting the specified remedial goals for most of the sites. Example successes include:

- Meeting aquifer cleanup goals in one or more zones at the site

  At Des Moines, the cleanup goals for the off-site plume were achieved within two years of startup of the remediation system. P&T continues to maintain an inward hydraulic gradient and to remediate on-site groundwater. The aquifer at the site is a relatively homogeneous formation of sand and gravel that has a relatively high conductivity.

- Reducing the size of a contaminated plume

  At Odessa I, the total plume area was reduced approximately 44 percent in two years (from 1994 to 1996). On several occasions, the groundwater extraction system was modified to improve efficiency.

- Reducing the concentrations of contaminants within a plume

  At United Chrome, average concentrations of chromium were reduced in the upper aquifer from more than 1,900 to 18 mg/L over nine years, and in the deep aquifer from 1.4 to 0.11 mg/L over six years. On several occasions, the groundwater extraction system was modified to target the more highly contaminated areas of the plume.

- Removing contaminant mass from a plume

  At French, Ltd., the P&T system removed approximately 517,000 pounds of contaminant (measured as total organic carbon) from January 1992 through December 1995. The mass was removed through aggressive pumping of groundwater that contained relatively high concentrations of contaminants (hundreds of mg/L) from more than 100 recovery wells.

- Achieving containment of a plume

  At City Industries, the contaminated groundwater plume has been contained hydraulically since the P&T system was put on line in 1994.

It is important to note that groundwater cleanup is ongoing at most of the case study sites; therefore, the system performance presented in this report does not represent the final performance to be achieved in remediating each of the sites. As discussed earlier, the data presented in the case studies are generally available through late 1997 or early 1998.

5.0 COST OF REMEDIAL SYSTEMS AT 28 CASE STUDY SITES

This section discusses the costs of the remedial systems at the 28 case study sites and unit costs for the groundwater cleanups at these sites.

The costs for the sites typically were reported as capital costs, operation and maintenance (operating) costs, remedial design costs, and other costs. For the purpose of this report, calculated unit costs are provided as average annual operating cost, capital cost per 1,000 gallons treated per year, and average annual operating cost per 1,000 gallons treated per year. Average annual operating cost as a percentage of capital cost is also presented. Assumptions used in reporting cost data are summarized below.

- Capital and operating costs were highly variable from site to site with key cost drivers, including variable monitoring requirements, significant system modifications needed, and size and complexity of the remedial systems
- The following three types of unit costs were calculated for each site:
  - Average operating cost per year of operation
  - Capital cost per 1,000 gallons treated per year
  - Average annual operating cost per 1,000 gallons treated per year

- Cost data presented in the case study reports were based on data provided by EPA remedial project managers, site owners, or vendors. The costs presented in this report are based on the cost data in these case study reports. In addition, updated cost data received in May 1999 for several of the sites (*Baird and McGuire, Libby, French Ltd., United Chrome, Sylvester/Gilson Road, Western Processing*) was included in this report. When actual cost data were not available, site contacts provided estimates based on the best data available at the time.

- Groundwater cleanup is ongoing at most of the sites; therefore, the operating costs (and in some cases the capital costs) do not represent the total to be spent to remediate a site. The data presented here generally are current as of late 1997 or early 1998, with 1999 data available for the sites identified above.

- Because groundwater cleanup is ongoing at most of the sites and the total time necessary to complete cleanup of a site was not known, a net present value (NPV) of the remedial costs for the sites was not calculated for this report. The systems in the 28 case studies had been operating for as few as 2 years and as long as 11 years. While many feasibility studies conducted under Superfund assume a 30-year duration to estimate the cost of a P&T remedy, the use of this timeframe was not considered to be applicable for this report because the two completed projects were completed in 3.5 and 7 years.

- Capital and operating costs were extracted from cost data provided in the case studies based on the Recommended Cost Format in *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* [4]. Capital costs included: technology mobilization, setup, and demobilization; planning and preparation; site work; equipment and appurtenances; startup and testing; and other technology capital costs. Operating costs included: labor; materials; utilities and fuel; equipment ownership, rental, or lease; performance testing and analysis (although compliance testing was often not separated out); and other technology operating costs. Source controls, RI/FS, and system design costs were not included as capital or operating costs. However, VCBs used for hydraulic control were included as capital costs.

- As previously discussed in Section 3.1, PRBs may differ in form and purpose from P&T and PRB systems, and unit costs for sites at which PRBs were used are shown separately from costs for sites at which P&T was used. PRBs treat only the groundwater that passes through the barrier, while P&T actively extracts groundwater from an aquifer. Therefore, the volume of groundwater treated by a PRB will be relatively less than by a P&T system for the same size plume.

Cost Data

Exhibit 5-1 presents the cost data for cleanup of contaminated groundwater at each of the case study sites. The table also identifies the major factors that influenced costs at each of the sites. Exhibit 5-2 summarizes overall remedial costs and unit costs for P&T and PRB sites, respectively, including minimum, maximum, average, and median costs for each of the two groups individually and combined.

Capital costs per P&T site ranged from approximately $250,000 (*Gold Coast*) to $15 million (*Western Processing* and *French, Ltd.*), and average annual operating costs ranged from approximately $90,000 (*MSWP*) to $4.4 million (*Western Processing*). Average annual operating costs ranged from 2.9 to 56 percent of the capital costs. The median capital cost was $1.9 million and the median average annual operating cost was $190,000; with median unit costs of $96 of capital cost per average 1,000 gallons of groundwater treated per year and $18 of average annual operating cost per average 1,000 gallons of groundwater treated per year.

Based on three sites, capital costs per PRB site ranged from approximately $370,000 (*Moffett*) to $600,000 (*Intersil [PRB]*), and average annual operating costs per PRB site ranged from approximately $26,000 (*Moffett*) to $95,000 (*Intersil [PRB]*). Average annual operating costs ranged from 6.9 to 17 percent of the capital costs. For the PRB systems, the approximate median capital cost was $500,000 and the median average annual operating cost was $85,000; with median unit costs of $520 of capital cost per average 1,000 gallons of groundwater treated per year and $84 of average annual operating cost per average 1,000 gallons of groundwater treated per year.

The total remedial cost for each site was not projected, since the number of years in which each system has been operating and the progress of each system toward meeting remedial restoration goals vary from system to system.

Exhibit 5-1: Summary of Cost Data for 28 Sites[1,2,3]

Site Name and Location	Years of Operation (with data available)	Average 1,000 Gallons Treated per Year	Capital Cost ($)	Average Operating Cost ($) Per Year	Average Operating Cost as Fraction of Capital Cost	Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Average Annual Operating Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Key Cost Drivers
P&T SITES								
Baird and McGuire, MA	3.8	21,000	11,000,000	2,000,000	0.18	530	97	Operating costs increased due to the need to monitoring for a wide range of contaminants and for several full-time operators to be onsite
City Industries, FL	3.0	50,000	1,200,000	170,000	0.14	23	3.3	Optimized pump rates; biofouling of air stripper increased system downtime
Des Moines, IA	8.8	554,000	1,600,000	110,000	0.07	2.9	0.21	Unit costs reflect economies of scale
Firestone, CA	6.8	266,000	4,100,000	1,300,000	0.31	15	4.9	Frequent modifications to system were required; cost of analysis and data management were high
French, Ltd. ,TX	4.0	76,000	15,000,000	3,400,000	0.21	200	43	Large system incorporating P&T and ISB; oversight costs were high
Gold Coast, FL	3.7	22,000	250,000	120,000	0.49	11	5.6	Optimized extraction wells; P&T system required less than four years to clean up site
Intersil (P&T), CA	7.3	5,000	330,000	140,000	0.43	65	28	Groundwater extraction system was expanded after three years of operation, likely increasing operating costs
JMT, NY	9.6	5,200	880,000	150,000	0.17	170	29	Modifications of treatment system increased capital costs 35 percent; system consisted of one extraction well

Table Continued...

Exhibit 5-1: Summary of Cost Data for 28 Sites[1,2,3]

Site Name and Location	Years of Operation (with data available)	Average 1,000 Gallons Treated per Year	Capital Cost ($)	Average Operating Cost ($) Per Year	Average Operating Cost as Fraction of Capital Cost	Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Average Annual Operating Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Key Cost Drivers
Keefe, NH	4.1	11,000	1,600,000	240,000	0.15	140	21	Optimization of the system pumping rates increased mass removal efficiency
King of Prussia, NJ	2.7	57,000	2,000,000	390,000	0.19	36	6.8	Electrochemical treatment increased costs
LaSalle, IL	4.4	5,200	5,300,000	190,000	0.03	1,000	36	Complex mixture of contaminants and DNAPL contributed to elevated capital costs
Libby, MT	5.3	2,900	3,000,000	500,000	0.17	1,000	170	Chemical costs (e.g., hydrogen peroxide) were high for *in situ* bioremediation; monitoring, sampling, and analysis costs were high at the beginning of the project
MSWP, AR	8.3	12,000	470,000	91,000	0.19	38	7.4	Use of fabric filters increased operating life of GAC units
Mystery Bridge, WY	3.6	54,000	310,000	170,000	0.56	5.7	3.2	Low concentrations in groundwater
Odessa I ,TX	4.2	30,000	2,000,000	190,000	0.10	65	6.3	ROD required that ferrous iron be produced onsite electrochemically, limiting number of appropriate vendors and increasing capital costs
Odessa II, TX	4.1	30,000	2,000,000	140,000	0.07	65	4.6	ROD required that ferrous iron be produced onsite electrochemically, limiting number of appropriate vendors and increasing capital costs

Table Continued...

Exhibit 5-1: Summary of Cost Data for 28 Sites[1,2,3]

Site Name and Location	Years of Operation (with data available)	Average 1,000 Gallons Treated per Year	Capital Cost ($)	Average Operating Cost ($) Per Year	Average Operating Cost as Fraction of Capital Cost	Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Average Annual Operating Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Key Cost Drivers
Old Mill, OH	7.8	1,700	1,600,000	210,000	0.13	960	130	Modifications to the system increased capital costs 22 percent
SCRDI Dixiana, SC	4.6	4,500	1,800,000	94,000	0.05	410	21	PRP made major modifications to the remedial system; relatively low contaminant concentration
Site A, NY	1.3	6,700	1,400,000	290,000	0.20	210	43	Use of skid-mounted modular equipment reduced capital costs; treatment system included air sparging and *in situ* bioremediation
Sol Lynn, TX	3.0	4,300	2,100,000	150,000	0.07	490	34	Complex hydrogeology increased capital costs
Solid State, MO	4.2	62,000	930,000	370,000	0.40	15	6	Capital costs do not include costs for installation of four deep extraction wells installed as part of RI/FS
Solvent Recovery Service, CT	2.9	11,000	4,400,000	400,000	0.09	390	36	Presence of DNAPL contributed to elevated capital and operating costs
Sylvester/Gilson Road, NH	9.5	126,000	7,200,000	1,900,000	0.27	57	15	Several full-time operators were on site 24 hours per day, high costs for fuel oil to operate the vapor incinerator used for air emission control
U.S. Aviex, MI	3.4	96,000	1,400,000	180,000	0.13	15	1.9	Optimization of interim P&T system before final remedy reduced costs

Table Continued...

Exhibit 5-1: Summary of Cost Data for 28 Sites[1,2,3]

Site Name and Location	Years of Operation (with data available)	Average 1,000 Gallons Treated per Year	Capital Cost ($)	Average Operating Cost ($) Per Year	Average Operating Cost as Fraction of Capital Cost	Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Average Annual Operating Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	Key Cost Drivers
United Chrome, OR	8.6	7,200	3,300,000	96,000	0.03	460	13	Modular treatment system used initially, reducing costs
Western Processing, WA	8.2	119,000	15,000,000	4,400,000 (4)	0.30	130 (4)	37 (4)	Initially used large complex system with over 200 vacuum well points, 24-hour oversight required; frequent maintenance to control iron precipitate buildup
PRB SITES								
Intersil (PRB), CA	1.8	1,100	600,000	95,000	0.16	520	83	P&T was replaced by PRB, reducing operating cost (see above)
Moffett, CA	1.2	200	370,000	26,000	0.07	1,600	110	Demonstration-scale project; increased performance monitoring was required for technology validation
USCG Center, NC	1.0	2,600	500,000	85,000	0.17	190	33	Use of PRB was estimated to save $4 million over a typical P&T system

Note:

1 Groundwater cleanups are ongoing at most sites; data presented here generally are current of late 1997 or early 1998.

2 Capital and operating costs were extracted from costs provided in the case studies based on the Recommended Cost Format in *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* [4]. Source controls, RI/FS, and system design costs were not included as capital or operating costs.

3 Cost data shown in the case study reports were based on data provided by EPA remedial project managers, site owners, or vendors. The costs presented in this report are based on the total costs available at the time the case study report for the site was prepared and updated cost data received in May 1999 for several of the sites (*Baird and McGuire, Libby, French Ltd., United Chrome, Sylvester/Gilson Road, Western Processing*). When actual cost data were not available, site contacts provided estimates based on the best data available at the time.

4 The P&T system at Western processing was changed in response to a change in the remedial goals at the site from aquifer cleanup to containment. The modified system pumped less than half of the water pumped by the original system. However, for this report, data were not available to determine the cost implications of the system modification.

Table Continued...

Exhibit 5-2: Summary of Remedial Cost and Unit Cost Data for 28 Sites[1,2,3]

Cost Category	P&T Sites (26 sites)				PRB Sites (3 sites)				All Sites (28 sites)			
	Range			Median *Average*	Range			Median *Average*	Range			Median *Average*
Years of System Operation (with data available)	1.3	-	9.6	4.2 *5.3*	1.0	-	1.8	1.2 *1.3*	1.0	-	9.6	4.1 *4.9*
Average Volume of Groundwater Treated Per Year (1,000 Gallons)	1,700	-	550,000	21,000 *63,000*	230	-	2,600	1,100 *1,300*	230	-	550,000	12,000 *57,000*
Total Capital Cost ($)	250,000	-	15,000,000	1,900,000 *3,500,000*	370,000	-	600,000	500,00 *490,000*	250,000	-	15,000,000	1,600,000 *3,200,000*
Average Operating Cost Per Year ($)	91,000	-	4,400,000	190,000 *670,000*	26,000	-	95,000	85,000 *69,000*	26,000	-	4,400,000	180,000 *610,000*
Average Operating Cost Fraction of Capital Cost	0.03	-	0.56	0.17 *0.20*	0.07	-	0.17	0.16 *0.13*	0.03	-	0.56	0.17 *0.19*
Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)	2.9	-	1,000	96 *250*	192	-	1,600	520 *780*	2.9	-	1,600	140 *310*
Average Annual Operating Cost Volume of Groundwater Treated Per Year ($/1,000 Gallons)	0.21	-	170	18 *31*	33	-	110	84 *76*	0.21	-	170	21 *36*

Notes:

1 Groundwater cleanups are ongoing at most sites; data presented here generally are cumulative as of late 1997 or early 1998.

2 Capital and operating costs were extracted from costs provided in the case studies based on the Recommended Cost Format in *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* [4]. Source controls, RI/FS, and system design costs were not included as capital or operating costs.

3 Cost data shown in the case study reports were based on data provided by EPA remedial project managers, site owners, or vendors. The costs presented in this report are based on the total costs available at the time the case study report for the site was prepared and updated cost data received in May 1999 for several of the sites (*Baird and McGuire, Libby, French Ltd., United Chrome, Sylvester/Gilson Road, Western Processing*). When actual cost data were not available, site contacts provided estimates based on the best data available at the time.

Calculated Unit Costs

Calculated unit costs are used to compare and contrast remediation technologies. Although the basis and methodology for calculation of unit costs for site cleanups are still a matter of some debate, some unit costs can be used to compare costs and performance at ongoing and completed cleanup efforts and in identifying cost-efficient remedial strategies for future cleanups. For this report, the following three types of unit costs were calculated for each site:

- Average operating cost per year of operation
- Capital cost per 1,000 gallons of groundwater treated per year
- Average annual operating cost per 1,000 gallons of groundwater treated per year

Those unit costs, along with their ranges, averages, and medians are summarized in Exhibits 5-1 and 5-2 and depicted in Exhibits 5-3, 5-4, and 5-5, respectively. The three unit costs summarized for the case study sites are described briefly below.

Average Operating Cost per Year of Operation

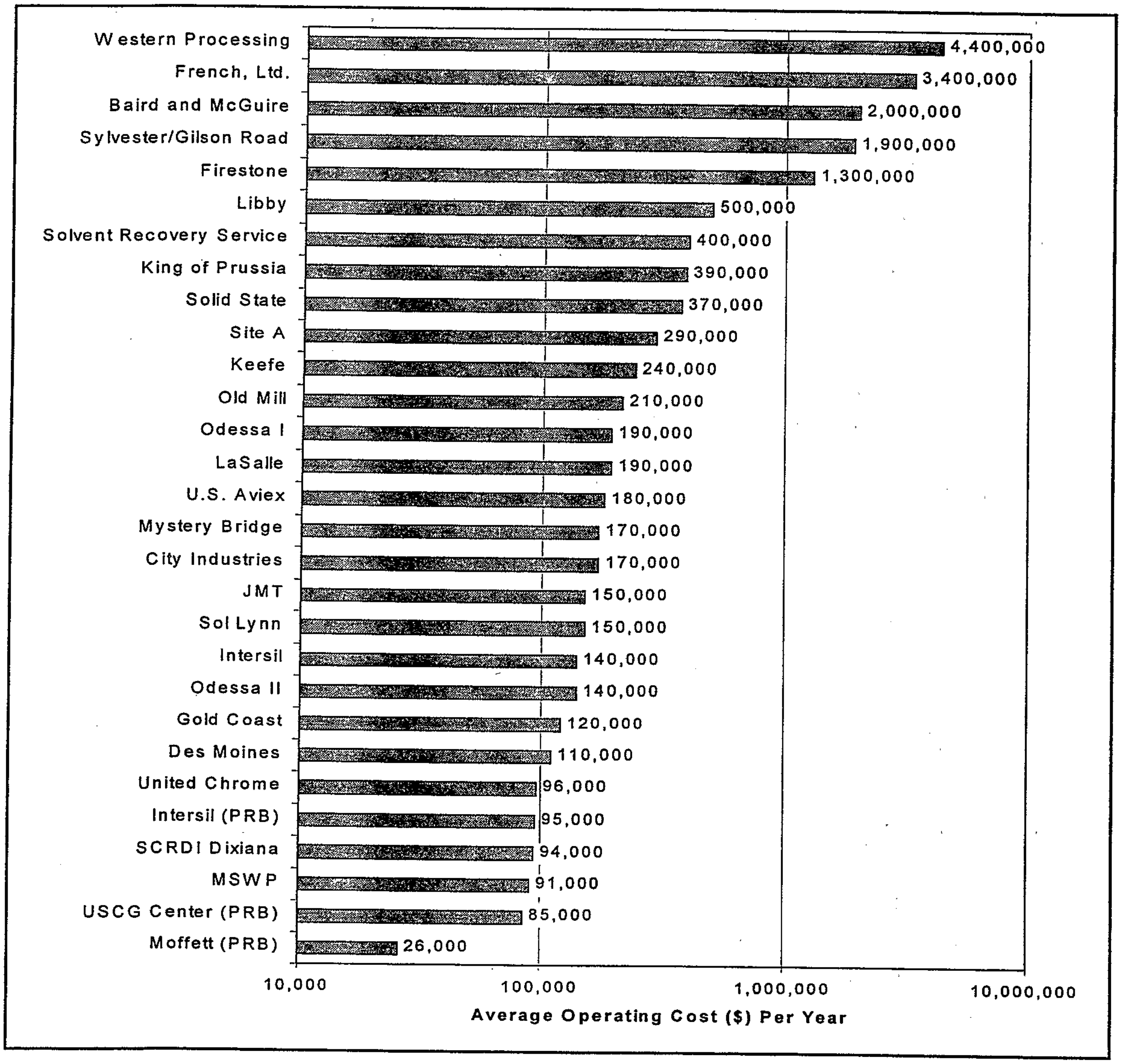
The average operating cost per year is determined by the throughput of the system and the treatment processes required to treat the extracted groundwater, as well as the operating efficiency of the system. Since a breakdown of annual operating costs by year was not available for most of the sites, the change in operating costs over the life of a site's remediation system could not be evaluated for the purposes of this report. The average annual operating costs were calculated by dividing the total operating cost to date by the number of years represented by that cost.

> *At SCRDI Dixiana, where approximately 40 gpm were pumped from 15 wells through a relatively simple system and discharged to a POTW, the average annual operating cost was $94,000 over 4.5 years. At French, Ltd., where approximately 190 gpm were pumped from more than 100 wells through a more complex treatment system before being reinjected into the aquifer, the average annual operating cost was more than $3.4 million per year over 4 years.*

Capital Cost per 1,000 Gallons of Groundwater Treated Per Year

The capital cost per 1,000 gallons treated per year represents the relative costs of installing remedial systems of varying capacity. This unit cost is influenced by factors such as the aquifer complexity (which influences the size and complexity of the system needed to extract the contaminated groundwater), the types of contaminants targeted for treatment at the site (which influences the treatment plant components needed to remove the contaminants), the water and air discharge limits for the particular site (which is also factor into the treatment plant components needed), and restoration goals (which reflects the difference between sites where a large volume of groundwater is treated over a relatively short time frame to clean up an aquifer versus pumping at a lesser rate to prevent a contaminated plume from migrating from the site).

Exhibit 5-3: Average Operating Cost Per Year at 28 Sites



The following example illustrates the effect of the aquifer complexity and treatment plant requirements on the capital cost per 1,000 gallons of groundwater treated annually.

> *At the Gold Coast site, groundwater in a relatively shallow and homogeneous aquifer contaminated with TCE was extracted and treated by an air stripper alone before it was discharged to surface water. The capital cost was $11 per 1,000 gallons of water treated. This compares with a cost of $1,020 per 1,000 gallons of water treated at the LaSalle Site, where groundwater was extracted via a horizontal pumping regime and was treated for a complex range of contaminants by a much more complex system. The system consisted of two air strippers, both vapor and liquid-phase GAC, oil/water separation, and pH adjustment.*

Exhibit 5-4: Capital Cost Per 1,000 Gallons of Groundwater Treated Per Year

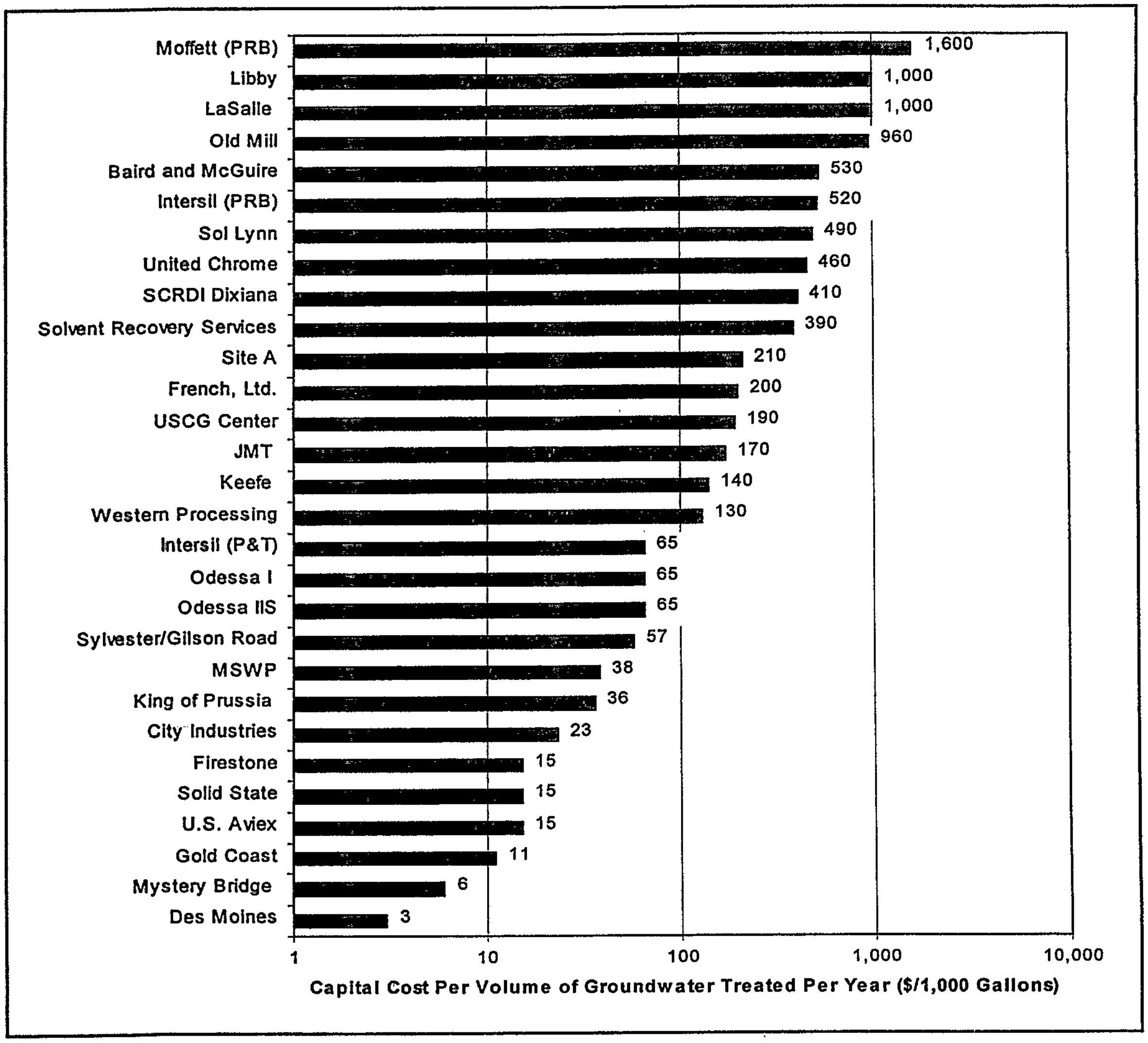
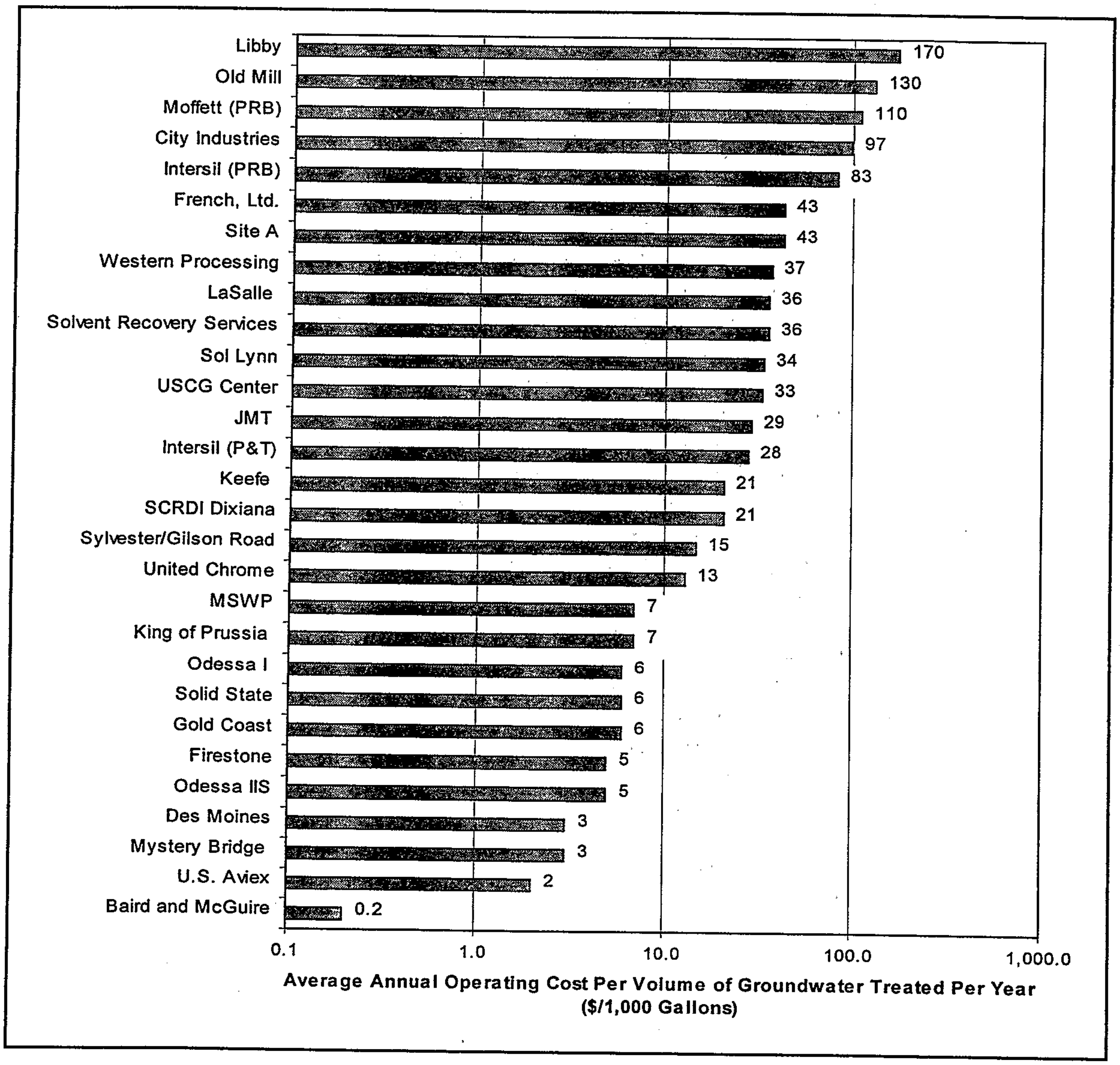


Exhibit 5-5: Average Annual Operating Cost per 1,000 Gallons of Groundwater Treated Per Year



Average Annual Operating Cost Per 1,000 Gallons of Groundwater Treated Per Year

The average annual operating cost per 1,000 gallons of groundwater treated per year represents the relative costs to operate systems of various capacities and complexities. Similar to the capital cost per 1,000 gallons of groundwater treated per year, this unit cost is highly dependent on site-specific factors such as the aquifer complexity, the types of contaminants targeted for treatment, the water and air discharge limits, and the restoration goals.

The following example illustrates the effect of the complexity of a site treatment system on average annual operating cost per 1,000 gallons of groundwater treated per year.

> *At Des Moines over 500 million gallons of groundwater were treated per year using a relatively simple system consisting of an air stripper for an average annual operating cost of $0.21 per 1,000 gallons of groundwater treated annually. Conversely, at Libby, 2.9 million gallons of groundwater were treated per year using a complex remediation system consisting of oil/water separation, nutrient addition, and bioreactors for an average annual operating cost of $173 per 1,000 gallons of groundwater treated annually.*

In general, systems that treat a relatively large volume of groundwater per year will cost less in both capital and annual operating costs per 1,000 gallons of groundwater treated than a similar system that treats a smaller volume of groundwater per year. While no specific correlation could be derived based on the available information, the following example shows this trend.

> *The treatment systems at Des Moines, City Industries, and Mystery Bridge consisted of P&T using air stripping as aboveground treatment. Des Moines treated a relatively larger volume of groundwater annually. The following table summarizes some of the data for these sites.*

Site Name	Average Volume of Groundwater Treated Annually (1,000 Gallons)	Average Annual Operating Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons)
Des Moines, IA	554,000	0.21
City Industries, FL	50,000	3.3
Mystery Bridge, WY	54,000	3.2

> *The average annual operating cost per volume of groundwater treated annually exemplifies the above trend.*

6.0 FACTORS THAT AFFECTED COST AND PERFORMANCE OF REMEDIAL SYSTEMS AT 28 CASE STUDY SITES

The factors that affected cost and performance at the 28 case study sites vary and are specific to each site. This section discusses the key factors that affected cost and performance of the groundwater cleanup at the case study sites identified from the case studies and industry knowledge about groundwater remediation. The factors have been grouped into the categories summarized in Exhibit 6-1.

- The factors that affected cost and performance at the 28 case study sites vary and are specific to each site
- No single factor was found to be the most important factor in determining cost and performance of groundwater cleanup projects

Exhibit 6-1: Factors Affecting Cost and Performance of Groundwater Remediation Systems

Category	Factors
Source control factors	Presence of NAPL; application and timing of source controls
Hydrogeologic factors	Properties of the aquifer; contamination of more than one aquifer; influence of surface water on aquifer; influence of adjacent groundwater production wells on aquifer
Contaminant property factors	Treatability of the contaminant; fate and transport properties of the contaminant
Extent of contamination factors	Area and depth of contaminated plume; concentrations of contaminant within the plume
Remedial goal factors	Restoration of the aquifer rather than plume; MCL rather than less-stringent cleanup levels; cleanup of the entire aquifer rather than partial cleanup; time allowed for cleanup
System design and operation factors	System downtime; system optimization; amount and type of monitoring performed; use of *in situ* technology

Each of the categories is discussed below; specific examples of how each factor affected cost or performance of the groundwater cleanup systems at the case study sites are also presented.

Source Control Factors

Sources of groundwater contamination vary from surface discharges to buried wastes. When source material comes in contact with groundwater, contaminants begin to dissolve and move into the groundwater by advection and dispersion mechanisms. In addition, contaminant sources in the vadose zone may act as continuing sources of groundwater contamination via leaching of contaminants onto storm water recharge that passes through the contaminated zone. Biodegradation and volatilization also may contribute to the destruction or dispersion of contaminants. However, in many cases, the mechanisms may have a negligible impact. The solubilities of many common contaminants (such as chlorinated solvents) are relatively low, and sources of those contaminants may remain in the subsurface for extended periods of time. EPA has concluded that one of the most effective means of remediating a site at which contaminated groundwater is present is to remove, or at least isolate, the source material from the groundwater. The source controls implemented at the case study sites (see Exhibit 3-2) include such methods as removal of hot spots (soil), soil vapor extraction, capping, and installation of VCBs.

NAPL has been observed or suspected to be a source of groundwater contamination at a majority of the case study sites (see Exhibit 2-7). Of the 28 sites, NAPLs were observed or suspected to be present at 18. At twelve of the sites, only DNAPL was present; at three, only LNAPL was present; and at another three both DNAPL and LNAPL were present.

At several sites (such as *French Ltd., SRS,* and *Western Processing*), efforts were made to remove or isolate the NAPL from contact with the groundwater. Such efforts often involved significant capital expenditures.

> *At Western Processing, both DNAPL and LNAPL were observed in the groundwater. A slurry wall was constructed around the site to contain the plume and help achieve the cleanup goals within a limited amount of time. The slurry wall required capital expenditures of approximately $1.4 million.*

If NAPL was not removed or isolated, the groundwater remediation efforts often were hindered.

> *At Solvent Recovery Service, DNAPL is present in both the overburden and the bedrock aquifers, and is a source from which a dissolved plume continually forms. Despite three years of P&T operation, the complex hydrogeology and DNAPL present at this site have resulted in fluctuating concentrations of total VOCs in the groundwater. Site representatives indicated that they plan to apply for a technical impracticability (TI) waiver because of the presence of the persistent source of DNAPL.*

Hydrogeologic Factors

Hydrogeologic factors that influence the cost and performance of groundwater remediation systems include the composition and hydraulic conductivity of a water-bearing layer; the depth to groundwater; contamination of more than one aquifer; vertical groundwater flow; the influence of surface water; and the influence of nearby groundwater production wells. These factors can affect the complexity of the groundwater remediation system as well as the ability of the system to meet the remedial goals at a site.

This report presents information about the hydrogeologic conditions at the 28 subject sites (see Exhibit 2-8). The hydraulic conductivity of the contaminated water-bearing layer(s) at the sites ranged from 0.023 ft/day to 1,200 ft/day, a range of more than six orders of magnitude. The hydraulic conductivity also often varied within an individual site, such as *United Chrome*, where the hydraulic conductivity in the upper aquifer was two orders of magnitude less than in the lower aquifer. At more than one-half of the sites, contamination was present in more than one water-bearing layer or aquifer. Seven of the sites exhibited vertical groundwater flow, 13 were influenced by adjacent bodies of surface water, and production wells (municipal or otherwise) were located in the vicinity of each of eight of the sites. Reported depths of the water table ranged from zero (at ground surface) to 45 feet below ground surface.

The following examples illustrate specific cases hydrogeological factors affected the cost or performance of the groundwater remediation technology implemented at a site.

Hydraulic Conductivity

At JMT, the hydraulic conductivity in the contaminated bedrock aquifer was relatively low (0.65 ft/day). To increase hydraulic conductivity, controlled blasting was carried out to create an artificial fracture zone, which served as an interceptor drain in the bedrock around the extraction well. While that approach increased the capital cost of the system (by an undetermined amount), it allowed effective extraction groundwater from the unit by one well screened in the new fracture zone.

Contamination of More Than One Aquifer

At SCRDI Dixiana, eight distinct soil layers have been identified within the upper 100 feet of soils, including five water-bearing units. Early site characterization work at the site misidentified the thicknesses and degrees of contamination of several of those units. Groundwater extraction wells were installed based on the results of that early work. The wells were screened across two units, thereby presenting a pathway for contaminants to migrate into a previously uncontaminated aquifer. In addition, the contaminated shallow sand aquifer at the site was not identified until after the system had been installed, resulting in the need to modify the remedial system to address multiple contaminated aquifers.

Vertical Groundwater Flow

At Solid State, the groundwater system is a leaky artesian system in karst formations, with shallow and deep bedrock zones separated by a semi-confining shale layer. Groundwater flow at the site is vertical as well as lateral, a condition that has resulted in contamination of multiple aquifers and the need to extract groundwater at several depths.

Influence of Bodies of Surface Water

At Site A, the groundwater flow is subject to tidal influence in the upper few feet of the upper-most aquifer. Water levels at the site sometimes have risen, and SVE wells at the site have been flooded.

Influence of Groundwater Production Wells

At Des Moines, groundwater flow is to the southeast; however, earlier high-volume pumping from city wells may have affected the flow direction, facilitating the migration of the contaminant plume.

Contaminant Property Factors

The types and properties of the contaminants being treated at a site, such as whether the contaminant has a tendency to be removed with extracted groundwater or to stay adsorbed to subsurface soils, can affect the cost or performance of a remediation system. In addition, the properties of the contaminants determine what treatment technologies are appropriate and the complexity of the system required to treat contaminated groundwater *ex situ* or *in situ*. Examples of sites where the contaminants (see Exhibits 2-4 and 2-5) and the contaminant properties affected the cost or performance of the groundwater remediation are presented below.

Complex Mixture of Contaminants

At Sylvester/Gilson Road, contaminants included chlorinated solvents, such as methylene chloride; nonchlorinated organics, such as toluene and phenols; and the metal selenium. The mix of contaminants was treated above ground by a long series of operations, including pH adjustment, settling, neutralization, filtration, air stripping with vapor incineration, and biological treatment.

Single Contaminant That was Relatively Easy to Treat

At JMT, groundwater was contaminated with chlorinated solvents. The groundwater treatment system consisted of only an air stripper, which was capable of reducing contaminant concentrations to a level where the treated groundwater could be discharged to an adjacent surface water body.

Extent of Contamination Factors

Groundwater contamination concentrated in an isolated areal and vertical extent typically is easier and cheaper to remediate than the same mass of contaminant when it extends deeper and spreads out over a larger area. This factor affects the size of the extraction and treatment system and the system complexity in terms of the quantity of groundwater to be extracted from the aquifer and treated *ex situ*. The volumes of contaminant plumes at each of the sites are presented in Exhibit 2-6. The following examples show the effects of a relatively small and relatively large extent of contamination at which groundwater remediation has been completed.

At Gold Coast, the initial areal extent of the contaminant plume was estimated to be 0.87 acres, and the initial volume of the plume was estimated to be less than 3 million gallons. The site was remediated at a cost of less than $700,000.

At the Former Firestone facility, the initial areal extent of plume was estimated to be 100 acres (1,300 feet wide and 3,400 feet long), with an initial volume of as much as 2.9 billion gallons. The cost to remediate this site was nearly $13,000,000.

Remedial Goal Factors

Remedial goal factors that may affect the cost and performance of a site cleanup include the stringency of the cleanup levels, the types of remedial goals, the types of performance requirements that have been established for the remediation as well as the system complexity required to meet these goals. The following remedial goal factors can influence the volume or areal extent of groundwater that must be treated, the type of treatment train that may be used, or the length of time that a system has to be operated.

- Stringency of the cleanup levels
  - maximum contaminant levels
  - approved alternate concentration limits
  - risk factors
  - other criteria
- Types of remedial goals
  - aquifer restoration
  - aquifer restoration and containment
  - other restoration goals
- Types of performance requirements
  - treated wastewater discharge limits
  - air emission limits

More stringent cleanup levels can require more complex systems, longer periods of operation, and larger volumes of groundwater to be treated. The type or stringency of the performance goals (treatment of extracted groundwater and/or air emissions) affect the manner and the extent to which extracted groundwater or off-gas from the remediation system must be treated before discharge. The following examples show the effects of various remedial goals on the cost and performance of site cleanup.

Types of Remedial Goals

At Western Processing, an aggressive P&T system, consisting of more than 200 groundwater extraction points pumping approximately 265 gpm, was installed to pursue aquifer restorations goals. After approximately seven years of operation, an ESD was issued to change the focus of remediation from restoration to containment. As a result of this change, the system was modified to a system pumping approximately 80 gpm. This modification significantly reduced the operating cost for the system.

Performance Goals Established

At Solid State, the site engineer identified institutional constraints that restricted the operator's ability to reinject treated groundwater. Reinjection of groundwater may have been a more cost efficient method for the disposal of treated groundwater, and could have increased groundwater flow through the contaminated zone. This restriction is believed to have increased the time required for site remediation more than any other single factor.

In addition, as shown at the *French, Ltd.* site, different remedies specified in a site ROD can impact cost and performance.

> *Under the ROD for French Ltd., modeling was used as a basis to select natural attenuation as a component of the site remedy. Modeling showed that concentrations at the boundaries of the site would be acceptable after 10 years of natural attenuation, and that P&T, which was costing more than $3 million annually, could be terminated.*

System Design and Operation Factors

In addition to site characteristics and remedial goals, system design and operation can affect cost and performance during remediation. System operation factors include the amount of time the system is operational and the adequacy of the system design to handle the nature and extent of the contaminants. For example, the long percentages of downtime for a system (see Exhibit 3-5) or problems with system design can increase the cost of a site cleanup. Conversely, various efforts in system optimization at a site (as detailed in Exhibit 3-7) can reduce the cost of a site cleanup and/or improve the performance of a system. Described below are examples in which system operation factors affected the cost or performance at case study sites.

> System Downtime
>
> *At King of Prussia, the treatment system has been operational approximately 76 percent of the time. Downtime has been caused by several factors, including the need to shut the system down for two months to repair a crack in a filter, and has increased operating costs.*
>
> System Optimization and Modification
>
> *After two years of operation, site engineers at Keefe performed an optimization study. As a result, two new wells were installed at locations that would increase groundwater extraction rates. Also, two existing wells were taken off line. Both extraction rates and contaminant mass flux to the treatment system increased as a result of the modifications, leading to more efficient capture of the plume.*
>
> *When periodic groundwater monitoring results at MSWP indicated that aquifer cleanup goals were met in five extraction wells, pumping from these wells was stopped and the pumping rates from the other wells was adjusted to optimize system performance.*

Additionally, the use of *in situ* technologies such as air sparging, ISB, and PRBs (see Exhibits 3-2 and 3-4) can lower the cost and improve performance of a remedial system. Because only seven of the case study sites used *in situ* technologies, and similar technologies were used at very few of these sites, it is not possible to draw significant conclusions about the effect of using *in situ* technologies on the cost and performance of groundwater cleanups. However, two specific examples of the effects of using *in situ* technologies are described below.

> *At Intersil, the site owner replaced a P&T system that had been operating for eight years with a PRB system. The PRB system continued to remove contaminant mass and reduce concentrations of the contaminant in the aquifer, while minimizing the cost of treatment and returning the site to sellable or leasable condition.*

> *At Gold Coast, air sparging was used to mitigate elevated contaminant concentrations around one well that was in a suspected source area. Once the contaminant levels in this well were reduced, aquifer cleanup goals were able to be met, and the groundwater remediation system at the site was able to be shut down.*

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